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COMMAND AND CONTROL FOR DISTRIBUTED LETHALITY

by

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Exercising command and control (C2) during naval distributed lethality operations presents a complex system of systems (SOS) challenge in support of maritime control. Applying a model based systems engineering (MBSE) approach to C2 within the distributed lethality environment requires development of methodologies to provide definition and structure for existing operational concepts while providing conceptual growth space for new operational techniques. This study develops a systems architecture approach to defining the C2 models for decentralized and distributed command structures and proposes criteria for assessing functionality and impacts to the C2 of naval platforms during distributed lethality operations using MBSE. The C2 modeling for distributed lethality documents the interconnections and relationship of information flow and the system requirements for maintaining the interconnection links during a simulated operational deployment of an adaptive force package (AFP). This modeling structure provides for an architecture view of the functions and measures of effectiveness that provide criteria for decision making during the operational planning of a distributed lethality mission. Development of an initial architecture enables future modeling and architecture refinement through simulations of the C2 structure and further research into technologies and methods of effective communication systems.

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COMMAND AND CONTROL FOR DISTRIBUTED LETHALITY

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ABSTRACT

Exercising command and control (C2) during naval distributed lethality operations presents a complex system of systems (SOS) challenge in support of maritime control. Applying a model based systems engineering (MBSE) approach to C2 within the distributed lethality environment requires development of methodologies to provide definition and structure for existing operational concepts while providing conceptual growth space for new operational techniques. This study develops a systems architecture approach to defining the C2 models for decentralized and distributed command structures and proposes criteria for assessing functionality and impacts to the C2 of naval platforms during distributed lethality operations using MBSE. The C2 modeling for distributed lethality documents the interconnections and relationship of information flow and the system requirements for maintaining the interconnection links during a simulated operational deployment of an adaptive force package (AFP). This modeling structure provides for an architecture view of the functions and measures of effectiveness that provide criteria for decision making during the operational planning of a distributed lethality mission. Development of an initial architecture enables future modeling and architecture refinement through simulations of the C2 structure and further research into technologies and methods of effective communication systems.

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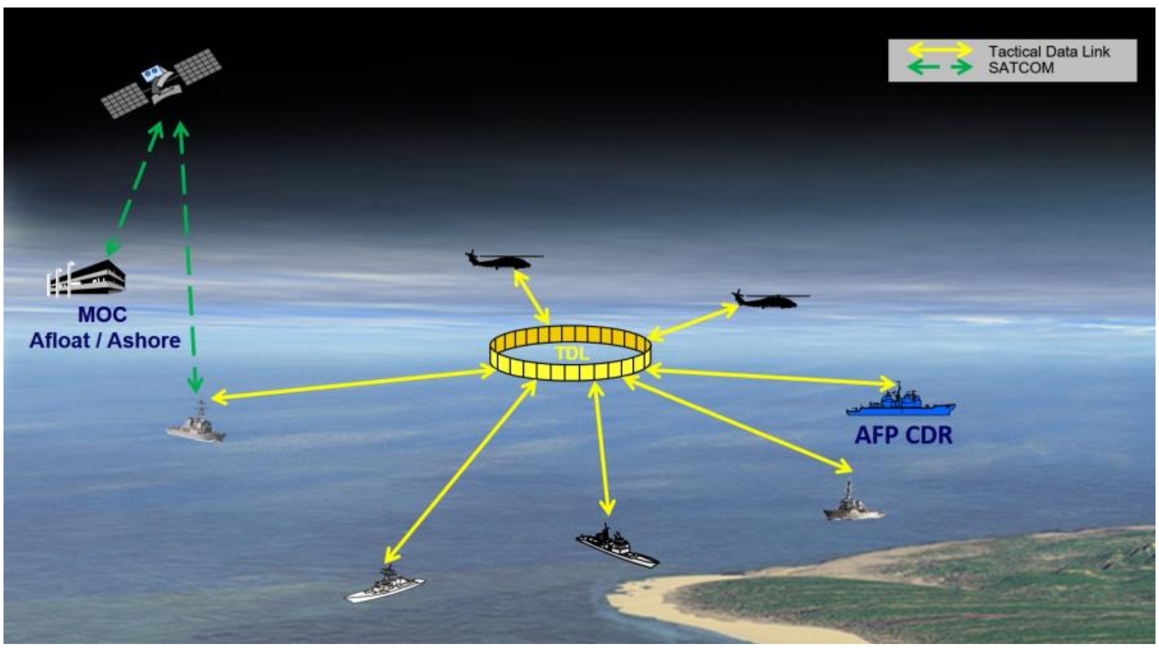
LIST OF ACRONYMS AND ABBREVIATIONS

AFP	adaptive force package
BOE	back of envelope
BLOS	beyond line of sight
C2	command and control
C2P	command and control processor
C3	command, control and communications
C4I	command, control, communications, computers, and intelligence
CDR	commander
CCDR	combatant commander
COMNAVSURFOR	Commander, Naval Surface Forces
CONOPS	concept of operations
CSG	carrier strike group
CTF	carrier task force
DAU	Defense Acquisition University
DDG	guided missile destroyer
DODAF	Department of Defense Architectural Framework
DOE	design of experiments
DOTMLPF	doctrine, organization, training, materiel, leadership, personnel, and facilities
EHF	extremely high frequency
EMCON	emissions control
ESSM	evolved sea sparrow missile
ETR	external time reference
FRAGORD	fragmentary order
JREAP	joint range extension application protocol
GCC	geographic combatant command
HF	high frequency
HHQ	higher headquarters
INCOSE	International Council on Systems Engineering
IP	internet protocol

LCS	littoral combat ship
LHA	landing helicopter assault
LHD	landing helicopter dock
LMMT	link monitoring and management tool
LOS	line of sight
MBSE	model based systems engineering
MDR	message dropout rate
MOC	maritime operations center
MOE	measures of effectiveness
MOP	measures of performance
MSP	message success percentage
OASuW	offensive anti-surface weapon/weapon
OPORD	operation order
OTC	officer in tactical command
OV	operational viewpoint
RF	radio frequency
ROE	rules of engagement
SAG	Surface Action Group
SE	system engineering
SEP	systems engineering process
SM	standard missile
SOS	system of systems
TLAM	Tomahawk land attack missile
USMC	United States Marine Corps
USN	United States Navy
USNS	United States Naval Ship

EXECUTIVE SUMMARY

In support of a Commander, Naval Surface Forces (COMNAVSURFOR) initiative regarding the distributed lethality concept, a Naval Postgraduate School Systems of Systems (SOS) systems engineering master's program capstone team applied model based system engineering (MBSE) with computer modeling and simulation to examine potential tactical command and control (C2) system architectures of an adaptive force package (AFP) operating in a distributed lethality scenario. The architecture is built around a South China Sea distributed lethality wargame study conducted by the Naval Postgraduate School's Operations Research Department.



Adaptive Force Package Command and Control Network Concept.

The geographical dispersion of naval forces operating under the distributed lethality concept introduces operational challenges to traditional C2 across an AFP due to the different characteristics of local and over the horizon communications architectures, the long distances required for communications, the anticipated disruption of satellite communications, and the relatively close proximity of opposing forces. Tactical C2 systems must be flexible to support changing communication architectures. Operational C2 must be flexible to work within the boundaries of the available communication architectures.

The use of MBSE and statistical analysis of computer simulation of C2 network architectures confirms the hypothesis that a distributed mesh architecture is the most robust for distributed lethality C2 networks. Model based systems engineering identifies possible efficiencies to the traditional C2 process model that can improve the effectiveness of C2 when operating within the constraints of distributed lethality. Statistical analysis of computer simulation of C2 networks and process models confirms the benefit. A systems architecture refinement to streamline the interactions of the operation order (OPORD) is recommended. This study moves the definition of the AFP OPORD into the SOS physical architecture for improved communications between the AFP and higher headquarters.

Review of available and near future advanced tactical data links finds no 100% solution in a single system. The distributed lethality AFP needs multiple tactical data link options to build a distributed mesh network architecture. The need for interoperability among all AFP platforms requires common data links. USN, USNS, joint and coalition forces will potentially participate in distributed lethality operations as part of an AFP.

Platforms without common datalinks must be modified to add this capability if they are to participate in the AFP C2 network. Advanced tactical data links must be interoperable on Link 16 and Link 22 to meet the joint and coalition interoperability requirement. AFP C2 systems should include provisions for the joint range extension application protocol (JREAP) for use when IP networks or satellite communications are available.

Distributed lethality AFP platforms will benefit from technology updates that improve automated network discovery by

- adding a link monitoring and management tool to identify and correct disruptions in tactical data link networks,
- utilizing an external time reference to aid tactical data link network synchronization, and

- employing smart command and control processor data routing to optimize routing and eliminate redundant messages.

Distributed lethality AFP platforms will also improve C2 network operations by adding directional antenna systems to the tactical data link systems. Directional antennas will shift from omnidirectional radio frequency radiation patterns to a controlled narrow beam path directed to other participants of the AFP C2 network. Benefits of directional antennas include lower probability of detection of the radiated signal, adding nulling patterns to reduce spectrum interference from hostile sources, and lower power output requirements for transmitters because a directional antenna focuses the RF signal using fewer radiating elements than an omnidirectional antenna.

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I. INTRODUCTION

A. BACKGROUND

The U.S. Navy introduced a new concept to improve combat efficiency via localized sea control through an increase in the offensive power of individual components of the surface force operating as part of a surface action group (SAG).

> Distributed lethality is the condition gained by increasing the offensive power of individual components of the surface force (cruisers, destroyers, littoral combat ships [LCSs], amphibious ships, and logistics ships) and then employing them in dispersed offensive formations known as "hunter-killer SAGs. (Rowden, Gumataotao and Fanta 2015)

Distributed lethality uses a concept called the adaptive force package (AFP) that is structured for subordinate commands to join efforts and strengths during coordinated maritime operations. Naval command and control (C2) must function within these AFPs when operating as part of a distributed lethality SAG. C2 as employed in operations with permissive communications environments was not architected to support this type of mission; therefore, a need exists to model C2 methods and architectures to better understand and ultimately improve the capability of naval forces operating under the distributed lethality concept.

B. PURPOSE

This research project examines the need to provide C2 to distributed naval forces. In order to understand the challenges of providing integrated support to the Navy fleet as it exercises this distributed lethality capability, it is essential to develop a framework, or systems architecture, that clearly defines and describes C2 challenges regarding distributed lethality through the broader application of model based systems engineering (MBSE) (Paulo 2016). This systems architecture serves as the centerpiece of the development, implementation, and analysis of the overall research effort, which includes operational simulation that allows the surface Navy to examine different options for providing C2 of naval forces operating in a distributed lethality mode. In support of a Commander, Naval Surface Forces (COMNAVSURFOR) initiative regarding the distributed lethality concept, this research seeks to optimize the tactical systems architecture for an AFP conducting a complex maritime mission while utilizing the distributed lethality concept. This systems architecture considers the integration of traditional C2 concepts with command, control, communications, computers, and intelligence (C4I) systems. This integrated C2 systems architecture serves to form a basis of an operational simulation to analyze possible distributed lethality C2 alternatives, both from a technical and doctrinal perspective; assess the different distributed lethality C2 alternatives regarding their impact on mission success; and model such concepts as the "fog of war," situational awareness, higher headquarters, and human error.

C. RESEARCH QUESTIONS

This paper addresses and answers the following questions:

- What is C2 support for distributed lethality in terms of the systems architecture?
- How can the Navy employ C2 support for distributed lethality?
- How effective are C2 systems architectures in support of distributed lethality?

D. SCOPE AND METHODOLOGY

This project defines, develops, and assesses C2 support for distributed lethality in terms of systems architecture development. By using MBSE as a means to allow an operational commander to decide on the most beneficial way in which to successfully provide C2 to naval forces operating in a distributed lethality environment, the distributed lethality systems architecture includes aspects of doctrine, organization, training, materiel, leadership, personnel, and facilities (DOTMLPF) (Paulo 2016). This effort is constrained to focusing on a specific operational concept, and subsequent mission and potential scenarios, which requires the deployment of one or more multi-platform AFP as necessary during the overall mission. This effort develops a functional architecture based on this operational concept involving a near-peer contested environment, a contested radio frequency (RF) spectrum, and additional research that helps shape the development of originating requirements regarding distributed lethality.

The functions and activities performed by the AFP to achieve mission success in the conduct of distributed lethality are defined through the development of a functional architecture as part of the overall systems architecture. Using aspects of DOTMLPF, this effort evaluates various physical solutions and considers options spanning doctrine, tactics, organizational command structure, the requirement for support ships or other support platforms, and the combinations of platforms and systems that can make up the AFPs.

E. STAKEHOLDER ANALYSIS

1. Stakeholder Identification

The maritime domain of warfare requires operational flexibility and adaptive platforms. International law governs the majority of the responses that nations (and by extension, their maritime services) may take in an armed conflict. The vagaries of territorial waters, exclusive economic zones, communications over vast distances, and the need for near-real-time coordination means that stakeholders for the distributed lethality concept can encompass a wide variety of entities. This distributed lethality C2 research project limits the range of possible stakeholders to "major stakeholders"—those stakeholders that will further develop or operate with this concept in an allied construct and are identified in Appendix D. The list of stakeholders is focused on three levels of command:

- the strategic level commander
- the tactical level commander
- the individual ship commander

2. Stakeholder Needs

The stakeholder needs originate from the need to control and dominate a specific area. An essential part of maintaining dominance in the maritime domain is the ability to communicate effectively and reliably between all of the forces controlling an area. Operational commanders define the methods to exercise C2 of naval forces operating across the maritime distributed lethality environment. The C2 need drives the determination of physical solutions across the breadth of available options and may include varying doctrine, tactics, structure of organization and command, the requirement for support ships or other support platforms, and the combinations of platforms and systems that make up the AFPs. The need is total operational environment control, which drives the C2 need for determining requirements to meet that need.

The operational commander needs to communicate their goals and understanding of the current environment, their desires for the future environment, and a range of permissible actions and outcomes that their tactical commanders can pursue. The tactical commander needs to execute their assigned tasks, and provide the operational commander with validation of the situation in the operational area, or indications that the operational model needs adjustment.

II. CONCEPT DEFINITION

A. COMMAND AND CONTROL

Command and control is defined as "the exercise of authority by a properly designated commander over assigned and attached forces in the accomplishment of the mission" (Department of Defense 2016). A nonprofessional's definition may be how military commanders issue directions to their warfighters in order to accomplish a given objective.

Maritime C2 is unique. By its very nature, a Navy ship operates very much alone. Before the age of radio communications, a ship's captain was relied upon to make life and death decisions on a regular basis without the aid of higher ranking or more experienced officers. It was not until the advent of satellite communications that ship commanders could be reached at all times in any location around the world. The U.S. Navy relies on a concept known as mission command due to vast distances and variations in weather and other communication issues that can prevent a maritime unit from contacting higher headquarters.

Mission command is "the conduct of military operations through decentralized execution based upon mission-type orders" (Department of Defense 2016). This approach to C2 demands that commanders of fleets give good, precise orders to their ship captains, and have enough trust in those captains to carry out their orders. Conversely, ship captains must exercise initiative and aggressiveness in the execution of those orders, but also must be willing and able to "call home" if unable to accomplish the mission.

1. The Levels of War

In the United States military doctrine, there are three levels of war: strategic, operational, and tactical. Refer to the illustration in Figure 1 for an overview of responsibilities and tasks at each level.

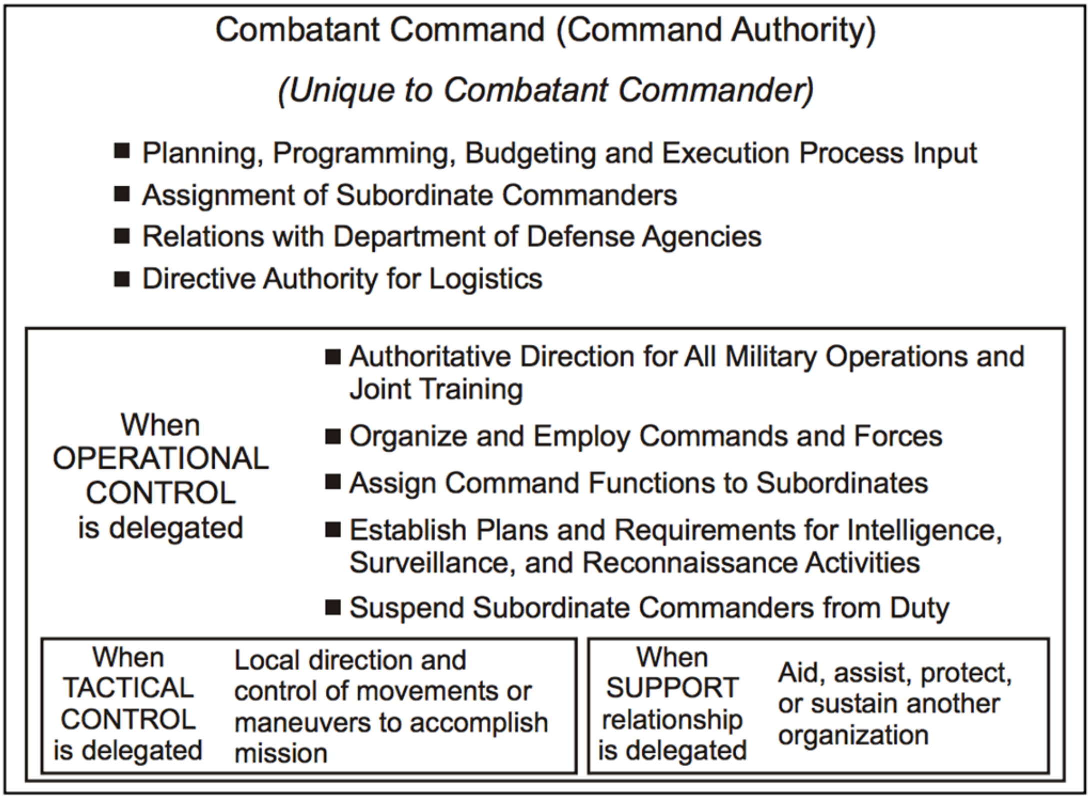

Figure 1. Combatant Command. Source: Department of the Navy (2010a).

In the strategic level of war, a nation or group of nations determines national or multinational objectives, provides guidance and uses national instruments of power to achieve these objectives. Top-level national officials—the president, secretary of defense, joint chiefs of staff, and combatant commanders—are the primary movers at this level. Strategic objectives are not just military in nature, but work in concert with diplomatic, intelligence, and political spheres to achieve national level objectives and goals.

The operational level of war links the strategic objectives laid out by high-level national officials to the actions required by tactical level units. The focus at the operational level is on military operations at the campaign level. In the maritime domain, operational level commanders are typically combatant commanders, their staffs, and their components. Combatant commanders are those commanders that are responsible for a geographic combatant command (GCC), and all the military operations that take place within their GCC. Component commanders are the senior service commanders within each GCC. Each combatant commander has a land, maritime, air, and special operations force commander underneath them that deals primarily with the domain specific requirements in their GCC. These component commanders are typically the senior service representatives for the Army, Air Force, Navy, Marines, and special operations force geographic components. Operational control is the authoritative direction for all military operations and joint training. It includes organization and employment of forces, and command functions (Department of the Navy 2010a).

The tactical level of war is the employment and ordered arrangement of forces in relation to each other (Department of the Navy 2010b). Tactical level commanders receive orders regarding an operation from their operational level commanders. These orders give the tactical commander the "who, what, where, when, and why" of an operation. It is up to the tactical commander to figure out the "how" of executing a given mission. There are also multiple tactical level commanders.

An AFP utilizing the distributed lethality doctrine in the accomplishment of a mission would operate at the tactical level of war. The investigation into C2 doctrine is therefore confined to this level. A critical component of distributed lethality is delegating some operational authorities down to the AFP Commander.

2. Organizing Ships: Tactical Command

Individual units are assigned to a task force by the officer in tactical command (OTC) of a maritime force, as illustrated in Figure 2. Each task force is then subdivided into various task groups, task units, and if required, task elements. Maritime forces are divided in this way to give commanders maximum flexibility in tasking via a mission type order and to provide a clear chain of command back up to the overall commander.

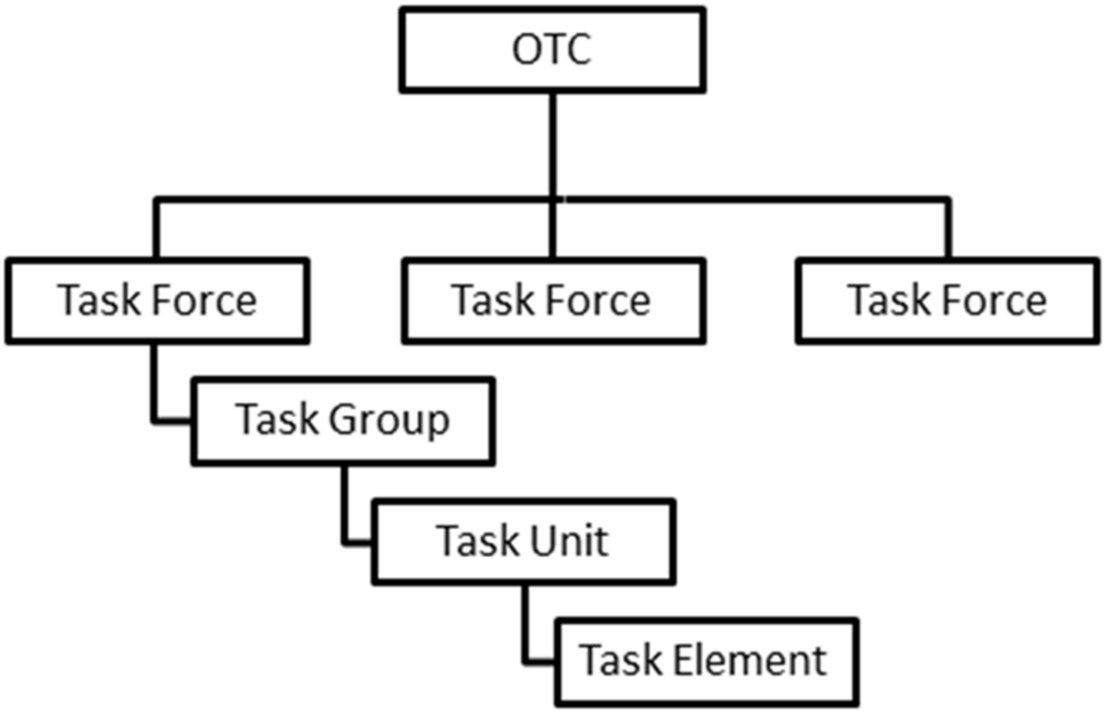

Figure 2. Levels of Tactical Command. Source: Department of the Navy (2010a).

3. The Third "C" of C2: Communications

The Navy Warfare Publication 3-56 defines the aim of command as, "to achieve the maximum operational and/or administrative effectiveness through direction, coordination, and control" (Department of the Navy 2010a). Command is inherently difficult in the maritime environment when units assigned to a single task force may be spread over hundreds or thousands of miles. To direct, coordinate with, and control units, an OTC must have the ability to communicate with units under their command. This requirement can be mitigated at the strategic and operational levels of war with proper planning and a well-written operations order. The tactical level has a much smaller time horizon in which to make decisions. The perils of tactical-level decisions (launching aircraft, releasing weapons, or maneuvering to a specific area) are immediate and dangerous to the units involved. To enable C2 at the tactical level, a third "C"—for communications—is required for effective C2, which results in the command, control, and communications (C3) acronym. The ability for tactical units to communicate, share information, and deconflict operations in real time is vital within the maritime domain. Execution of current Navy doctrine using a composite warfare commander, who is defined as the officer in tactical command of a naval task organization (Department of Defense 2016), is dependent upon real-time tactical communication.

B. DISTRIBUTED LETHALITY

The legacy concept of a naval commander operating in isolation from higher command was superseded by a networked concept of operations, made possible by tactical data links and global satellite communications. Reliable communications systems enable continuous communications between Navy ships at sea and higher command. The communications systems also facilitate data sharing for distribution of a common operational picture amongst ships and back to higher command. Forward deployed units may receive strategic tasking and enhanced situational awareness because of the ability to communicate with experts and senior decision makers located in a networked operations center at higher headquarters.

The essence of sea power is to exert control over the sea lines of communication; to do this, a naval force must be able to carry the fight to the enemy (Mahan 1949). Proliferation of technologies such as techniques for disruption of satellite communications, anti-ship ballistic and cruise missiles, and over-the-horizon radars have enabled near-peer armed forces (particularly China and Russia) to hold the traditional purveyor of U.S. Naval power, the carrier strike group (CSG), at risk at ranges beyond the CSG’s defensive weapons (Filipoff 2016). Rowden, Gumataotao, and Fanta developed the concept of hunter-killer surface action groups as a means to take the fight to the foe, which has since been more commonly discussed as distributed lethality.

This study distills distributed lethality as a doctrine of deploying multiple small groups of forces in AFPs across an area of operations to conduct operations against an enemy. The AFPs either can be tailored to create a specific set of effects, or can be established ad-hoc. The bulk of the units forming an AFP are surface combatants. The

AFP concept specifically allows for the incorporation of other platforms, such as aircraft, unpiloted vehicles, subsurface assets, supply ships, and other assets of opportunity.

Several characteristics are key to distributed lethality:

<u>Offensive in Nature</u>: Distributed lethality is a means to project naval power while countering the threats posed by the long-range weapons and sensors of potential adversaries. Establishing a time and space for offensive operations against a capable adversary necessitates a flexible means of massing firepower to overwhelm defenses in a given area. Shifting to a distributed lethality AFP structure creates a more complex targeting problem for adversaries while allowing the U.S. Navy more operational flexibility.

<u>Localized Sea Control</u>: In an engagement with a near-peer adversary near their shores, a typical scenario assumes that the enemy is proficient at the employment of long-range sensors and long-range weapons. The adversary also has modern, well-trained, and well-equipped forces operating in the maritime region that the U.S. Navy requires access. Distributed lethality does not require establishing unchallenged control or access to the adversary's waters before conducting operations or maintaining this control for an extended period. Distributed lethality focuses on techniques to allow the AFP to get in, accomplish a mission, and get out.

<u>Deceptive</u>: Distributed lethality allows for greater use of operational deception. By creating both false and real targets for a numerically superior adversary to investigate, distributed lethality forces the enemy to commit forces to chasing false targets, and allows AFP units greater opportunity to find, track, target, and destroy adversary units.

<u>Dispersed</u>: Distributed lethality seeks to reduce the density of U.S. forces by using advances in sensors and communications to cover more ocean area with fewer ships. This increases the adversary's search volume and decreases the opportunity for the adversary to engage the AFP into a decisive Mahanian fleet-on-fleet engagement (Mahan 1949).

<u>Rapid Re-tasking</u>: The OPORD for an AFP is one of the keys to the distributed lethality concept. By developing multiple courses of action in advance of an operation and by giving the AFP commanders clear tasking with well-defined decision points and

break points, the AFP can be rapidly re-tasked. Re-tasking may be initiated by detecting changes in the adversary's posture, by meeting completion conditions for a given section of the OPORD, or by a change in AFP capability.

USMC Integration: "A more fully integrated Marine Corps–surface force combat team will provide persistent presence that can influence and control events at sea and in the littorals, applying the right capability to the right target for the joint-force commander" (Rowden 2016). Distributed lethality employs all available offensive weapons systems. USMC integration enables the F-35B joint strike fighter to participate as sensor and weapon, and enables participation of ships supporting Marine expeditionary forces.

Limited Carrier Strike Group (CSG) Support: Distributed lethality was developed in response to improvements in long-range sensors and engagement capabilities that adversaries are fielding. One of the underlying tenants of distributed lethality is that an adversary's systems are tasked with finding and defeating U.S. Navy aircraft carriers in the early phases of a conflict (Center For Maritime International Security [CMISEC] 2016). Distributed lethality assumes that the traditional CSG structure is not employed until late in a conflict and that the AFP is operating only with systems organic to the AFP. Air support during the distributed lethality phase is limited to the aircraft onboard the platforms within the AFP.

Limited Self-Sustainment: Distributed lethality minimizes the number of high value units placed at risk. Distributed lethality missions are assumed to be short duration with major resupply happening outside of a contested area.

Provide Viable Targeting Data: Distributed lethality tactical targeting data is assumed to be generated and networked by sensors and communication systems organic to the AFP platforms.

Current or Near Future Resources: Very little in the development of new systems is proposed. Distributed lethality C2 can adapt with minimal equipment modification. Distributed lethality is largely an operational concept.

Force Adversary to React: Distributed lethality is an offensive posture designed specifically to force an adversary into a reactive mode. OPORDs that the adversary had in place before the initiation of a conflict must be challenged, allowing the U.S. Navy forces to operate as a cohesive whole while the adversary is forced to reconceive organizational and operational structure.

C. CONCEPT OF OPERATIONS

This report implements distributed lethality through four interrelated concepts: the AFP; localized C3 within the AFP; a robust operations order; and assured communications with higher headquarters, typically a maritime operations center (MOC) located ashore or afloat (onboard a large command level ship). These concepts are illustrated at a high level by the DODAF operational viewpoint (OV-1) in Figure 3. Satellite communications may be intermittent, isolated to one platform in the AFP, or completely nonexistent. A functioning tactical data link is essential for localized AFP C3. Command and control authority over the AFP must be local when reliable external communications are not available.

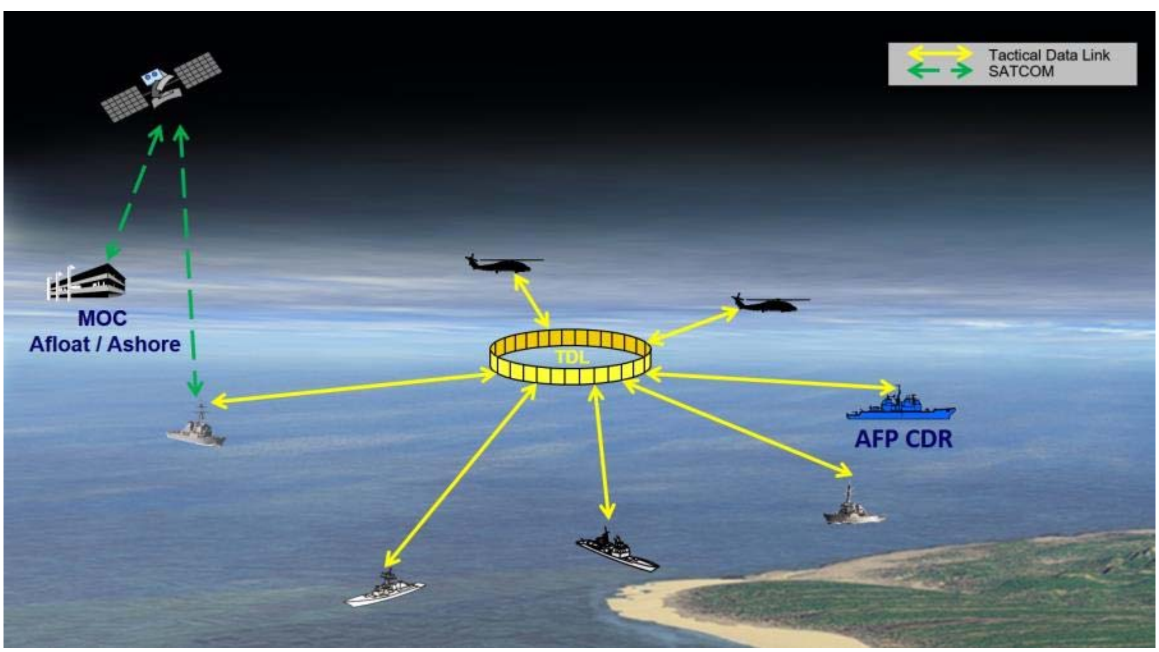

Figure 3. OV-1 AFP Concept of Operations.

The AFP is a task group of surface and subsurface combatants, USN auxiliary support ships (USNS), associated aircraft, and unmanned craft. Each AFP is tailored based on the platforms that are available for tasking and the mission to be accomplished. The AFP is assigned at the task group level; however, the command structure of the carrier task force (CTF) does not necessarily follow the joint warfare commander model.

The scenario in Figure 4 assumes that satellite communications across the AFP are denied by the adversary early into a conflict or that satellite communications are restricted to a single platform. Lack of reliable long-range communications to higher headquarters means that localized C3 is key to the success of the AFP. This study investigates if tactical datalinks organic to the AFP can allow sharing of enough tactical C3 information and weapons queueing to perform the mission. Tactical data links enable the AFP component commanding officers to fight their units as a whole by coordinating with the other units of the AFP to do tasks such as cooperative engagement or coordinated fires.

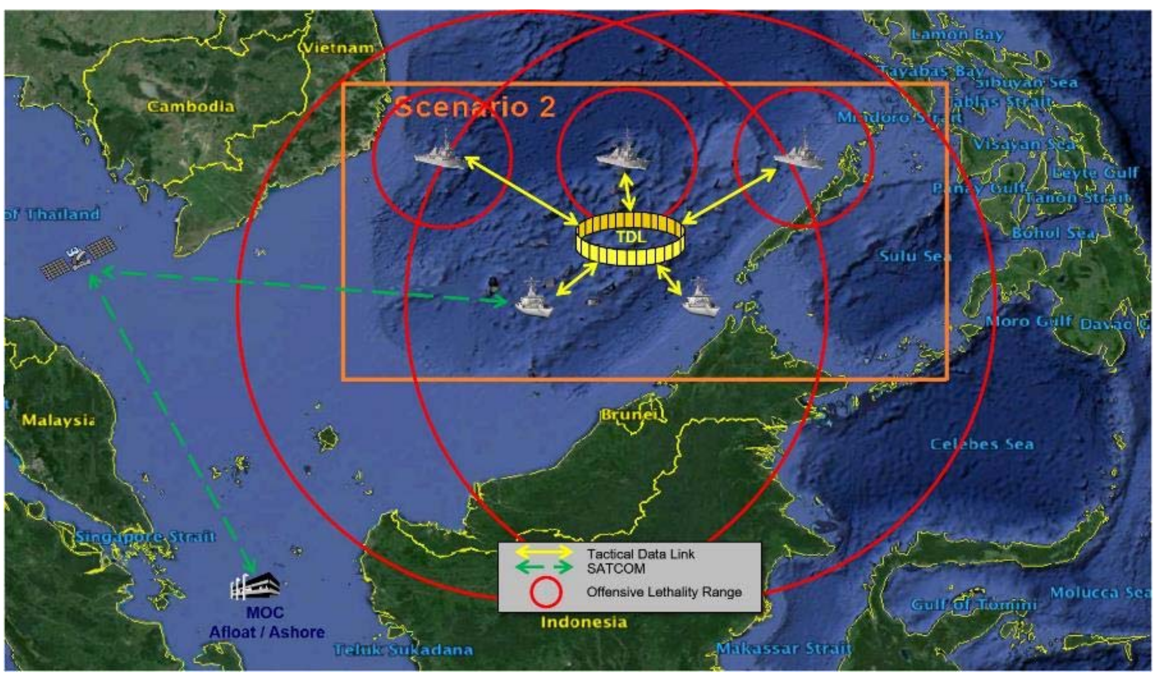

Figure 4. OV-1 AFP Scenario. Adapted from Orndorff et al. (2015).

The key innovation in the implementation of distributed lethality is the OPORD. The OPORD gives the AFP clear guidance on task group objectives, rules of engagement, commander's guidance, and targeting priorities. The intent of the OPORD is to provide the AFP commander with enough information before executing a mission that the AFP commander is allowed to proceed with operations described in the OPORD without further discussion with the ashore MOC (or CTF afloat MOC). The OPORD is be supplemented by fragmentary orders (FRAGORD) when necessary, which direct the AFP commander to execute a different portion of the mission, change targeting priorities, or return to base.

Figure 4 assumes that satellite communications are not available across the AFP early in a distributed lethality scenario and that reliable communications to a MOC are limited or nonexistent. Low bandwidth, time-late, message traffic between the MOC and the AFP may be available. Reliable exchange of information between the MOC and AFP is limited to short text messages. The AFP may be able to report general status at regular intervals, and to pass naval messages requesting clarification of commander's intent; however, passing large volumes of hi-fidelity data such as sensor feeds or sharing a common operational picture is not possible. Communications from the MOC to the AFP is limited to FRAGORDs, recall of the entire AFP, or short intelligence reports while the AFP is within the scenario operational area.

D. SCENARIOS

Scenario development builds upon prior distributed lethality wargame studies conducted by the Naval Postgraduate School's Operations Research Department during the Summer and Fall 2015 courses of "OA4604 Wargaming Applications" (Orndorff et al. 2015). The wargames examined distributed lethality operating in the eastern Mediterranean Sea and the South China Sea. The South China Sea wargame was selected to develop the base scenario model due to the regional complexity, remoteness from traditional centralized C2 maritime operations centers, and large operational area. The scenario is scalable to adapt to other possible distributed lethality AFP operating areas such as the Mediterranean Sea, other constrained waterways, or open ocean operations where the distributed lethality AFP may be operating as a single system or part of a larger strike group.

The 2016 deployment of destroyers USS Decatur (DDG-73), USS Momsen (DDG-92), and USS Spruance (DDG-111) (Larter 2016) operating in the South China Sea (Kelly 2016) demonstrated distributed lethality tactics using traditional remote centralized C2 while under orders from the U.S. Navy Third Fleet headquarters in San Diego, CA. Unclassified publicly available information about this deployment and the OA4606 wargames led the distributed lethality team to propose a notional scenario around an AFP consisting of six surface platforms.

1. Notional Scenario Development

The notional base scenario shown in Figure 5 builds upon the Fall 2015 OA4604 wargame (Orndorff et al. 2015) by adding six generic platforms to the area bounded by wargame scenario 2. Distributing the platforms for maximum coverage across the operational area places the platforms beyond the line-of-sight (LOS) horizon from the other AFP platforms. Tactical data links for C2 require beyond-line-of-sight (BLOS) capability for the AFP to maintain coordinated C2 with higher authority and among the members of the AFP. This connectivity could be achieved by one or more platforms connecting to a satellite network that provides long-haul C2 data transport between the AFP and a numbered fleet command center, such as Third Fleet headquarters in San Diego, CA.

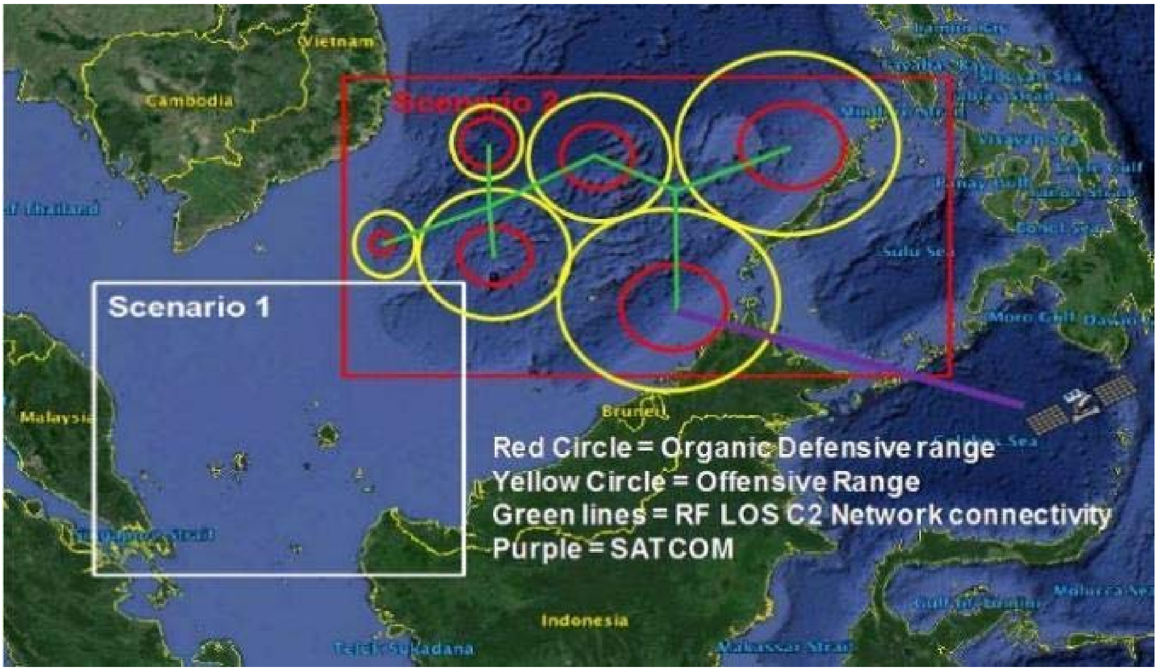

Figure 5. Notional Base Scenario — South China Sea. Adapted from Orndorff et al. (2015).

The example in Figure 5 shows a single platform with satellite connectivity and the AFP platforms communicating by line of sight networks with two airborne relays (airborne relays are at the central meeting points of the green lines). The platform with satellite connectivity would serve as the relay to the distant command center and therefore would be a single point of failure in this network and a high value target to adversaries. Exchanging C2 information between an ashore centralized command center to the most distant platform in the AFP requires multiple relay points and communications technologies that may not be reliable or functioning at all times over the entire AFP operational area.

The goal of the scenario is to exercise C2 information exchange and tactics in varying constructs that can be developed into a computer simulation model to compare the effectiveness and performance of different network topologies and tactics. The network concepts illustrated in Figure 6 (Baran 1964) were explained in a 1964 research paper by Paul Baran of the Rand Corporation. The distributed network topology is the foundation of the modern internet data routing architecture. Traditional U.S. Navy C2 hierarchies operate similarly to the centralized and decentralized network topology. A goal of scenario development is to explore possibilities of distributed C2 and compare it to the effectiveness of centralized and decentralized C2.

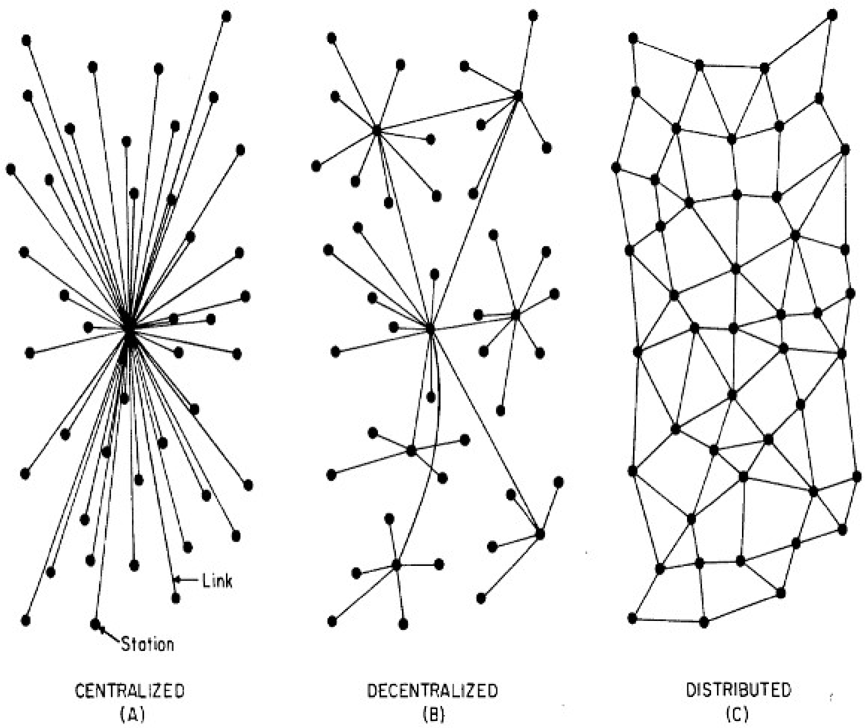

Figure 6. Centralized, Decentralized, and Distributed Networks. Source: Baran (1964).

The base scenario attempts to model the platforms shown in Figure 5 to establish a baseline network topology and simulated performance. The base scenario model is modified as shown in Figure 7, Figure 8, and Figure 9 to represent centralized, decentralized, and distributed networks.

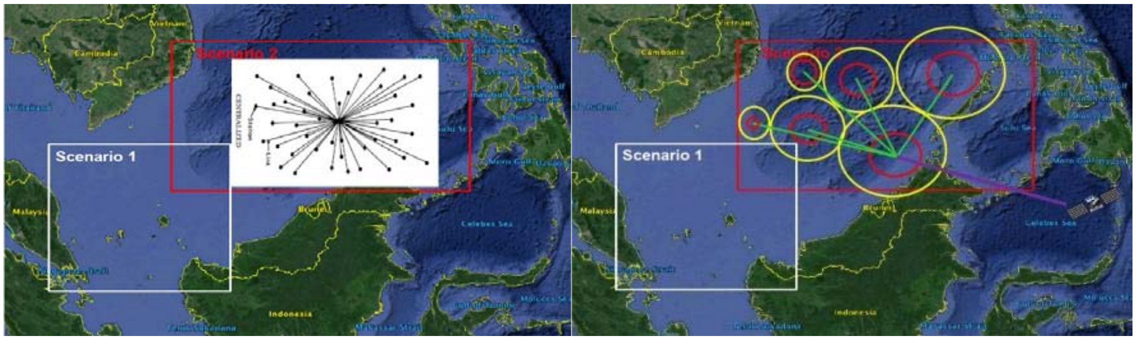

Figure 7. Centralized Network Scenario. Adapted from Orndorff et al. (2015); Baran (1964).

The centralized network requires a central node that controls network information flow among network nodes and has connectivity to all other nodes. All information must transverse the central node and loss of the central node halts network information exchange. In the tactical arena, this would be catastrophic to C2 of an AFP. The 1950s-era Link 11 tactical data link is a centralized C2 network that revolves around the network control station. Satellite networks are also centralized when only one satellite is available to the AFP.

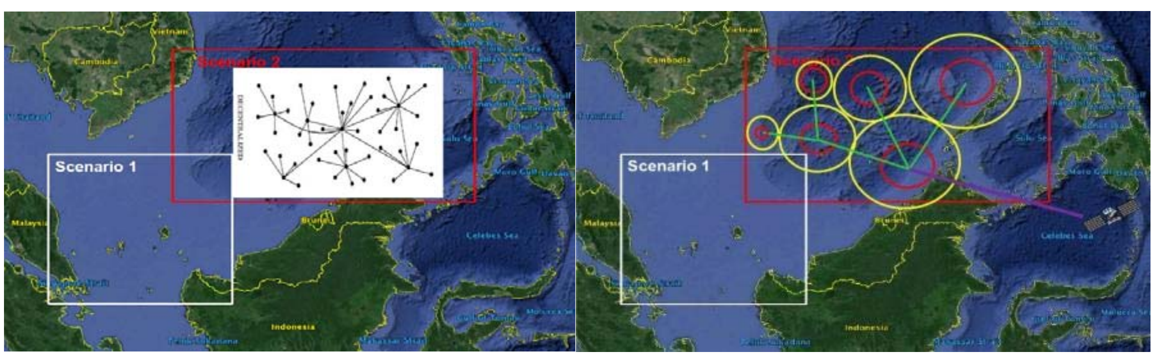

Figure 8. Decentralized Network Scenario. Adapted from Orndorff et al. (2015) and Baran (1964).

The decentralized network combines one or more centralized networks into a larger networked system of systems. A modern C2 tactical network that makes use of all available communications paths to function as a system of systems may operate in a decentralized fashion. Loss of a single central node degrades the network and AFP capability but does not disable the entire network. Nodes that were connected to a disabled node must recognize their loss of connectivity and reconfigure for connection to another node—if connectivity to another node is available. Nodes unable to reconnect become isolated from the C2 structure. Severity of node loss is a function of the role the node plays in the network and the AFP mission. In the tactical arena, this could be catastrophic to C2 of an AFP if the path to C2 authority is disrupted. Affect to the AFP mission by loss of the single node, as shown in Figure 8, is dependent upon the functions the connected platforms are performing and the needs of the operational scenario. Loss of the connection between the central nodes breaks the decentralized network into isolated to centralized networks.

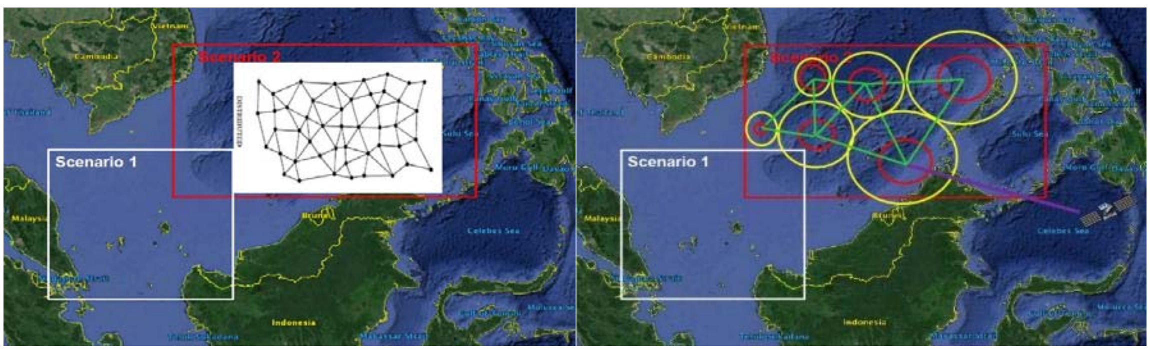

Figure 9. Distributed Network Scenario. Adapted from Orndorff et al. (2015); Baran (1964).

The distributed or mesh network can survive the loss of any node or network connection path. In the tactical arena, this should not be catastrophic to C2 of an AFP. Each node has two or more paths for C2 network connectivity. Loss of any single path allows the network to retain functionality within the AFP when the network C2 system architecture design functions via distributed C2 network paths. Loss of the single satellite path in Figure 9 only affects communications to nodes outside the local AFP. AFP systems architecture, tactics, and scenarios should consider cases where the AFP network is disconnected from satellite paths, or network nodes are radio silent under emission control protocols.

Modeling the differing network variations as scenarios enables performance comparisons and provides data to recommend the most effective network systems architecture to optimize networking technologies needed to build a seamless and survivable network that can be interoperable in the distributed lethality AFP scenarios. A goal of AFP scenario MBSE is to provide data for further analysis of system capabilities and to determine if current or planned architectures support or adapt to the distributed lethality mesh C2 networks and tactics, and if there are other capabilities (material or nonmaterial solutions) needed for distributed lethality C2.

2. Scenario Model Simulation Development

The distributed lethality command and control scenario models AFP 1 from scenario 2 of the Fall 2015 OA4604 wargame. As shown in Table 1, AFP 1 consists of three littoral combat ships (LCS) and two guided missile destroyers (DDG). The wargame gives the LCS an offensive anti-surface weapon (OASuW) with a range of 120 nautical miles (nmi) and the DDG a Tomahawk land attack missile (TLAM) equipped with notional surface warfare capable seeker. For simplicity of the distributed lethality scenario model, the notional OASuW Tomahawk range is assumed to be more than 1100 nmi.

Table 1. AFP in Base Scenario. Source: Orndorff et al. (2015).

Scenario 2: Adaptive Force Package

<table>
<tr><th>Red Forces</th><th colspan="3">Blue Forces
Choice of one Adaptive Force Package</th></tr>
<tr><td rowspan="2">1 x Carrier (with 12 x FS-7)
1 x Landing Craft
2 x Amphibious Vessels
5 x Destroyers
6 x Frigate
5 x Corvette
3 x Submarine
4 x Attack Aircraft
4 x Jammer Aircraft
2 x Coast Guard Cutters
2 x Coast Guard Patrol Crafts
2 x Groups of Fisherman Boats</td><td><u>AFP1</u>
3 x Littoral Combat Ship
2 x Destroyer</td><td><u>AFP2</u>
3 x Destroyer
12 x Attack Aircraft
1 x Amphibious Landing Craft</td><td><u>AFP3</u>
2 x Destroyer
2 x High Speed Vessel
12 x Small Missile Craft</td></tr>
<tr><td>1 x Recon Aircraft
1 x Destroyer</td><td>1 x Recon Aircraft
1 x Destroyer</td><td>1 x Recon Aircraft
1 x Destroyer</td></tr>
</table>

The width and height of the OA4604 wargame scenario 2 was estimated as 900 by 550 statute miles then rounded to 1000 by 500 nmi for ease of modeling the distributed lethality C2 scenario. DDG equipped with an 1100 nmi range notional OASuW Tomahawk can project power from any location inside the scenario box. AFP 2 with Landing Helicopter Assault (LHA)/Landing Helicopter Dock (LHD) is not modeled because the F-35B joint strike fighter extends the offensive range to 1000+ nmi (similar to the DDG with TLAM). Red forces are not modeled because they can be anywhere within the scenario area, while the location of red forces may deter blue forces from actively transmitting C2 data, the purpose of the simulations are to determine the influence centralized, decentralized, and distributed networks have on C2 when applied to a distributed lethality AFP. Additional scenario and platform assumptions are located in Appendix B.

The simplified base scenario in Figure 10 shows the 1000 by 500-mile area as an orange rectangle with red circles indicating the OASuW range of the LCS and DDG platforms.

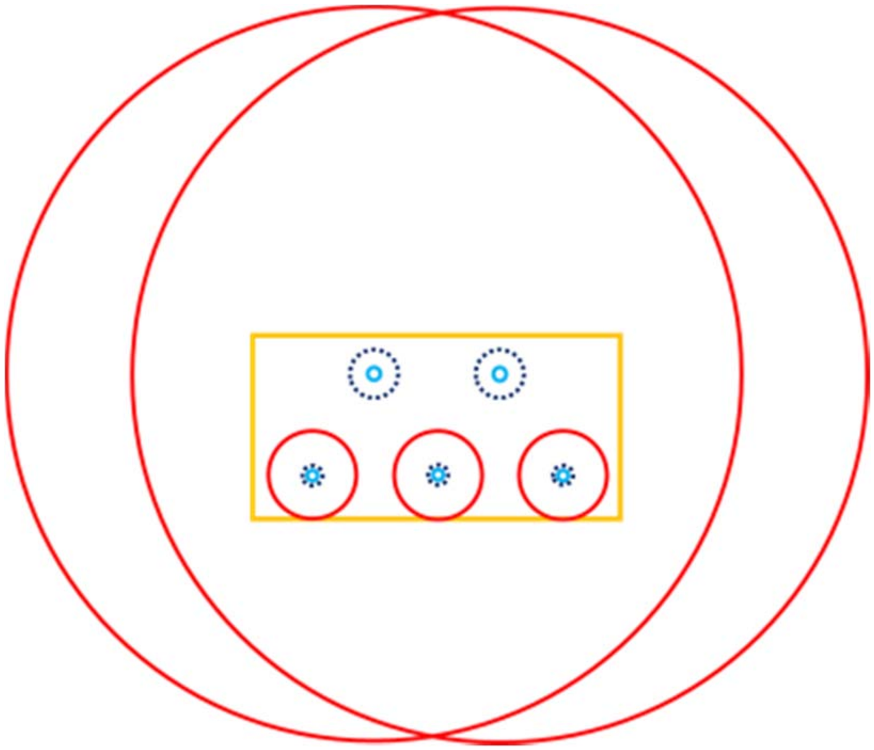

Figure 10. AFP 1 Scenario OASuW Range.

The platforms are at the center of each red range ring with cyan rings representing the line of sight to the horizon and dashed blue rings representing the range of defensive missiles. The line of sight range is calculated based upon estimated mast height. The LCS mast height is estimated at 100 feet, giving 14 miles to the horizon. The DDG mast height is estimated at 160 feet, giving 18 miles to the horizon. LCS armed with the RIM-162 evolved sea sparrow missile (ESSM) have a defensive range of 27 nmi. DDG armed with SM-2 standard missiles have a defensive range of 80 nmi. Sensor ranges are not modeled because they are assumed to be the operational range of embarked rotary wing aircraft. The MH-60 operational range is estimated at 460 nmi. With a five-platform AFP arranged as shown in Figure 10, the MH-60 can provide sensor coverage to any area within the scenario.

Distributing the AFP platforms to maximum OASuW coverage could produce the physical layout shown in Figure 11.This layout represents an ideal mesh network for a five platform AFP to support decentralized C2 with each platform having two or more network communication paths of equal distance to their nearest platforms, as represented by equilateral triangles with sides of 333 nmi. This configuration has two platforms (two LCS) with two paths, two platforms (both DDG) with three paths, and one platform (LCS) with four paths (for shorthand referred to as 2x2, 2x3, 1x4). The LCS are positioned 120 nmi from the lower boundary at equal intervals. LCS placement is the driving factor for AFP platform spacing due to the shorter OASuW strike ranges. DDG placement is secondary because of the long strike range of the notional OASuW TLAM.

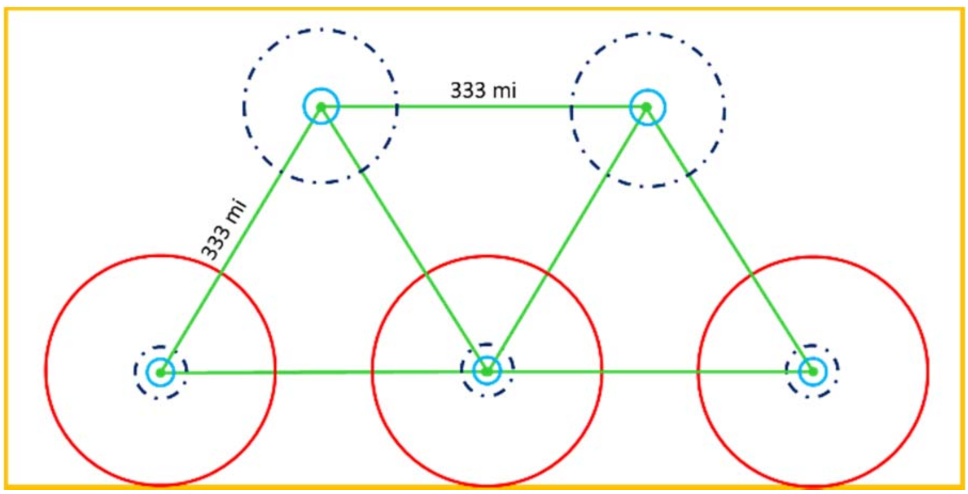

Figure 11. AFP 1 Scenario Platform Separation.

Figure 11 yields a minimum threshold communication range of 333 nmi. The objective communication range is 1118 nmi (calculated by $\sqrt{1000^2 + 500^2}$) for corner-to-corner communications if the platforms are permitted to navigate to any location within the 1000 x 500 nmi scenario boundary. Two options to support distributed lethality C2 at threshold or objective communication ranges are high frequency (HF) waveforms for BLOS or the use of an airborne node to relay LOS waveforms. Two airborne relays operating at 20,000 feet could provide coverage to the AFP. Relays are represented by shaded purple circles in Figure 12. The relays have a 200-mile line of sight range. A disadvantage using relays are the addition of a single point of failure in the network architecture. If one relay fails or is otherwise unavailable, two of the AFP platforms have no C2 communications path. Relays also increase the C2 message data transport cost by a small amount. Transport cost is a factor of point-to-point transport time, data processing time at each node, and the probability of message loss due to RF propagation range or spectrum interference. The ideal data transport networking waveform is a single point platform-to-platform.

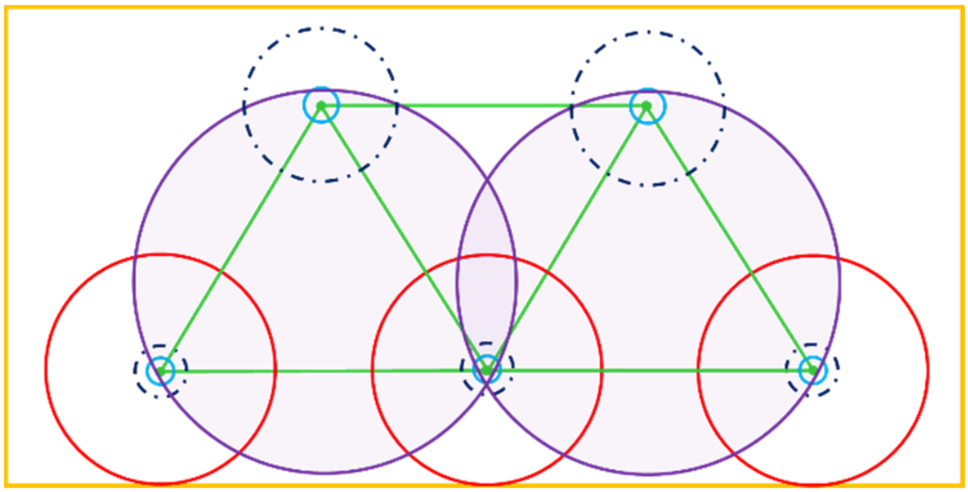

Figure 12. AFP 1 Scenario Platform with Airborne Relay.

Defensive range and sensor rages are not factors in this layout because the goal is to maximize OASuW coverage to distribute the lethality of the AFP. The AFP platform ranges could be decreased if overlapping offensive coverage or mutual defensive support is preferred for the mission.

By the year 2025, it is possible the LCS may have longer range offensive weapons (Osborn 2017). Figure 13 shows the LCS and DDG each with 200 nmi offensive range. The DDG illustrated in this configuration have standard missile – 6 (SM-6) capable OASuW (LaGrone 2017) with an estimated 200 nmi offensive range (IHS Global Limited 2016). The triangle geometries change, but the same pair of airborne relays at 20,000 feet continues to provide coverage. The purpose of Figure 13 is to illustrate communications ranges and offensive coverage of the scenario area when all five platforms have equal 200 nmi OASuW ranges. This scenario also represents an AFP consisting of any five generic platforms with 200 nmi OASuW range (making DDG and LCS interchangeable).

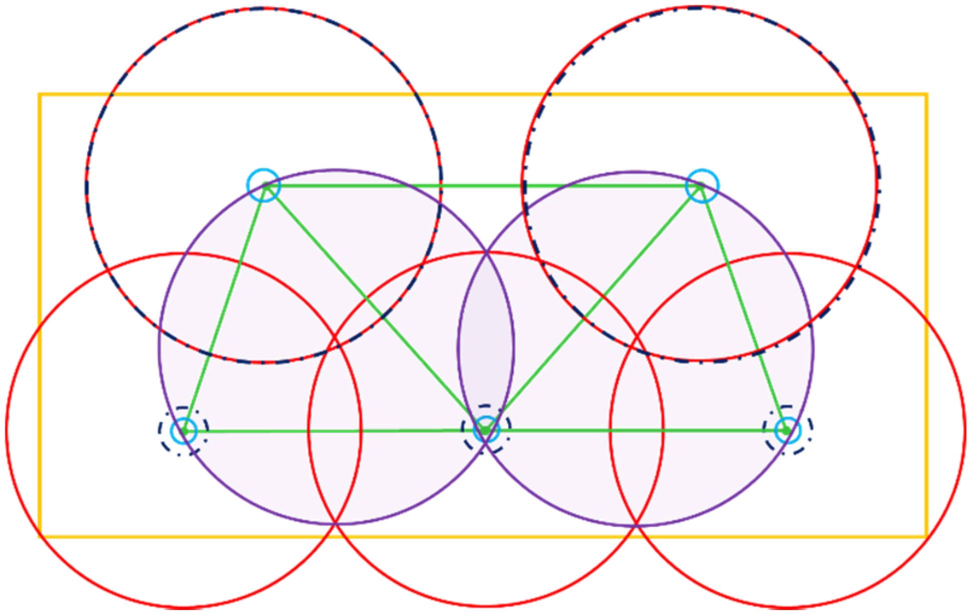

Figure 13. AFP 1 Scenario 2025 Notional OASuW Ranges.

Figure 14 removes the relay and range rings from Figure 13 to illustrate that ranges between LCS do not change when all five platforms have 200 nm OASuW range. The DDG can move further apart due to the change in OASuW range, but could also remain spaced at equal distances as shown previously in Figure 11. The notional OASuW Tomahawk is not shown in the 2025 scenarios, but it may remain on DDG if available. The presence or absence of the OASuW TLAM does not change the C2 communications architecture. The ranges of the notional 2025 scenario are not simulated because the goal of the simulation in this paper is to compare network types and their affect to C2 in the distributed lethality AFP. Note that the number of communication paths between the nodes is the same in Figure 14 and Figure 11. Figure 14 is shown to illustrate the minimal impact on distributed lethality C2 communications range if longer-range weapons are available to the LCS.

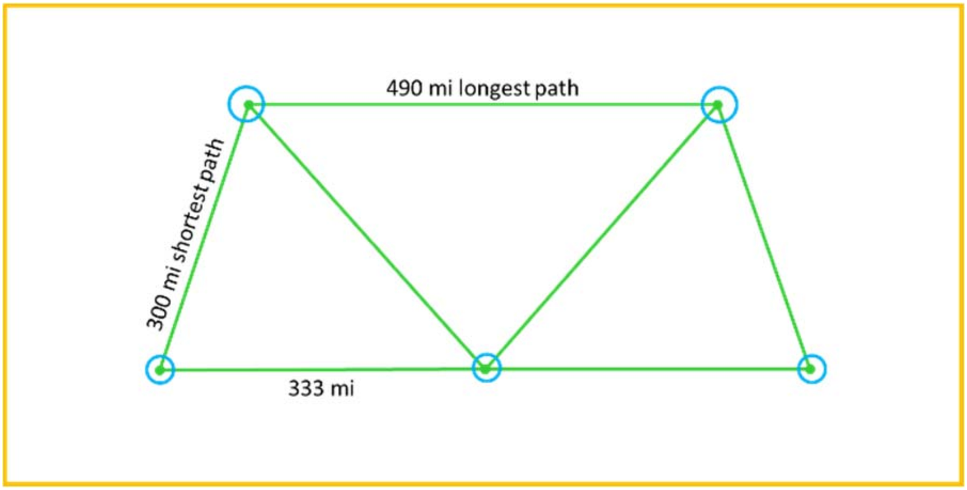

Figure 14. AFP 1 Scenario 2025 Notional Communication Ranges.

The worst-case communications distances for the AFP are illustrated in Figure 15. This configuration places LCS on three corners, one DDG on the fourth corner and one DDG in the center. This layout does not optimize the OASuW coverage within the scenario area. This configuration illustrates that one airborne relay operating at 150,000 feet, or two airborne relays operating at 50,000 feet are required for line of sight relays. Figure 15 is not simulated because the number of communication paths between nodes is potentially four paths at each node. Figure 15 is shown to reinforce the optimal C2 communications range of 1118 nmi and options for coverage with LOS waveforms.

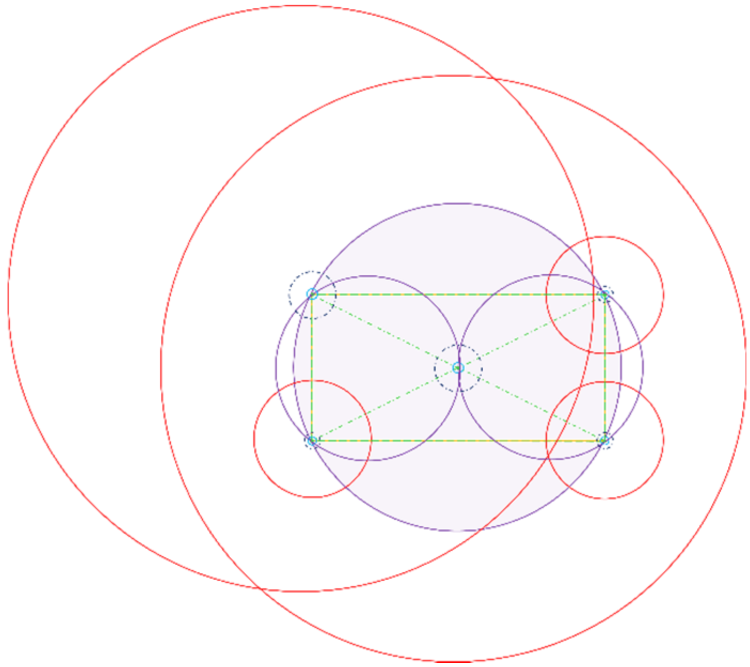

Figure 15. AFP 1 Scenario Worst-Case Communication Ranges.

An alternate scenario with the LCS across the diagonal shown in Figure 16 provides less than ideal communications because the node locations do not provide symmetric communication paths. This configuration may actually reduce the four platforms on the corners to only two possible mesh network paths (from 2x2, 2x3, 4x1 in Figure 11, to 4x2, 1x4), unless a long haul BLOS waveform is available to connect the corner platforms to a third node. If a viable long-haul waveform could be available, this would be the ideal configuration due to four of the nodes having three communications paths and the fifth node having four communications paths. Two airborne relays at 20,000 feet can provide coverage for LOS waveforms.

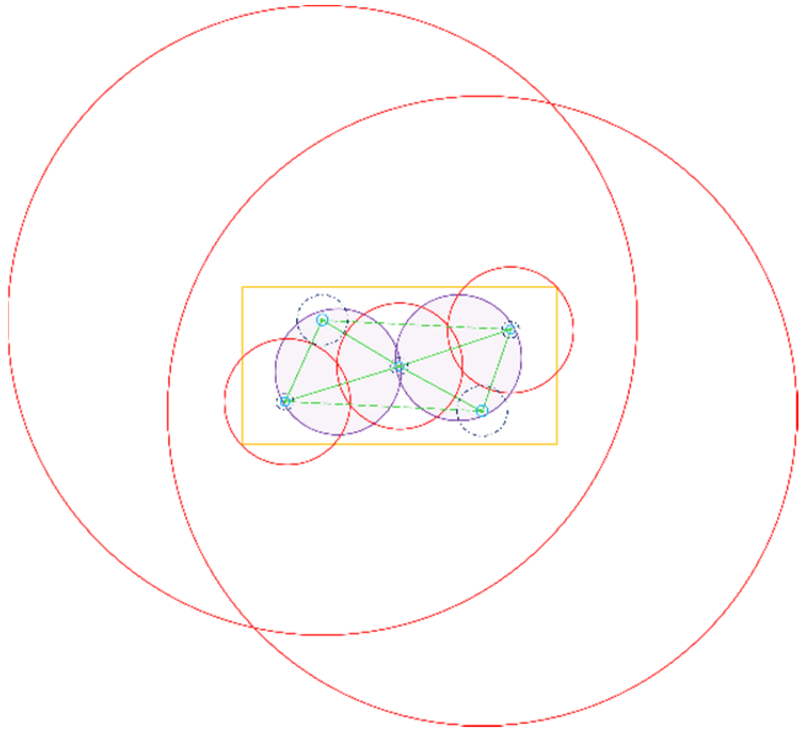

Figure 16. AFP 1 Scenario LCS Alternate Layout.

Based upon the scenario layouts in the previous figures, the base scenario for decentralized C2 in Figure 11 is selected for model development. This scenario remains valid if the notional 2025 OASuW ranges extend to 200 nmi for all platforms. Two platforms have two communications paths; two platforms have three communications paths, one platform has four communications paths (2x2, 2x3, 4x1). The platform with four paths may be the preferred C2 authority in the AFP due to the central location for C2 communications and the highest number of redundant paths; however, any platform in the network may assume the role of distributed lethality C2 authority. A five platform AFP in the Figure 11 configuration permits simulating the effects of two, three, or four redundant communication paths in the distributed lethality C2 environment. Five platforms are the minimal number to simulate the three network types of centralized, decentralized, and distributed. It is assumed that adding additional platforms or increasing redundant communication paths to five or more has little impact on the effectivity of distributed lethality C2.

3. Scenario C2 Networking Options

The Link 22 waveform (Northrop Grumman 2013) satisfies most requirements for distributed lethality C2 tactical data link networking. Link 22 does not satisfy the desire for a low probability of detection waveform when omnidirectional antennas are employed. The Link 16 waveform satisfies most requirements for distributed lethality C2 networking, except the need for BLOS range unless an airborne relay is employed. An external time reference (ETR) aids platforms operating in radio silence or with marginal network signal coverage to obtain and maintain network synchronization during distributed lethality C2 networking. Directional antenna systems can further reduce the probability of detection. Combining Link 16 and Link 22 with a smart router that performs the functions of a link monitoring and management tool (LMMT) can seamlessly route distributed lethality C2 data between tactical networks. Further research in these areas is recommended.

Internet protocol (IP) based networks are also an option for tactical data links within the AFP if a reliable networking waveform is available that meets the desired criteria for availability, BLOS range, data throughput, security, low probability of detection, low probability of intercept, resistance to jamming, and interoperability among potential AFP and coalition platforms.

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III. FUNCTIONAL ARCHITECTURE

A. FUNCTIONAL ARCHITECTURE ANALYSIS

Establishing a new concept of operations (CONOPS) for distributed lethality requires re-evaluation of the functional architecture used to execute the CONOPS. Since distributed lethality is being implemented in the near term, much of the physical architecture will involve ships, communications systems, and weapons that are already in the Navy inventory, with the innovation of distributed lethality being a new system of systems overlaying a new functional architecture atop the existing physical systems.

In order to ensure that there is traceability from the CONOPS through the distributed lethality AFP analyzed in Chapter V of this report, the project used a three-step process to develop requirements from the CONOPS, perform a functional decomposition on the C2 functions traced to the requirements architecture, and then allocate those functions to physical components in the adaptive force package. The researchers then analyzed alternate communications and command architectures to compare different approaches to operating an AFP.

The three-step process used in this study was a system of systems modification to the systems engineering process developed in the Defense Acquisition University (DAU) manual, *DOD Systems Engineering Fundamentals* (Systems Management College, Department of Defense 2001), as shown in Figure 17 and summarized as follows:

> The Systems Engineering Process (SEP) … transforms needs and requirements into a set of system product and process descriptions, generate information for decision makers, and provides input for the next level of development. …(T)he process includes: inputs and outputs; requirements analysis; functional analysis and allocation; requirements loop; synthesis; design loop; verification; and system analysis and control.

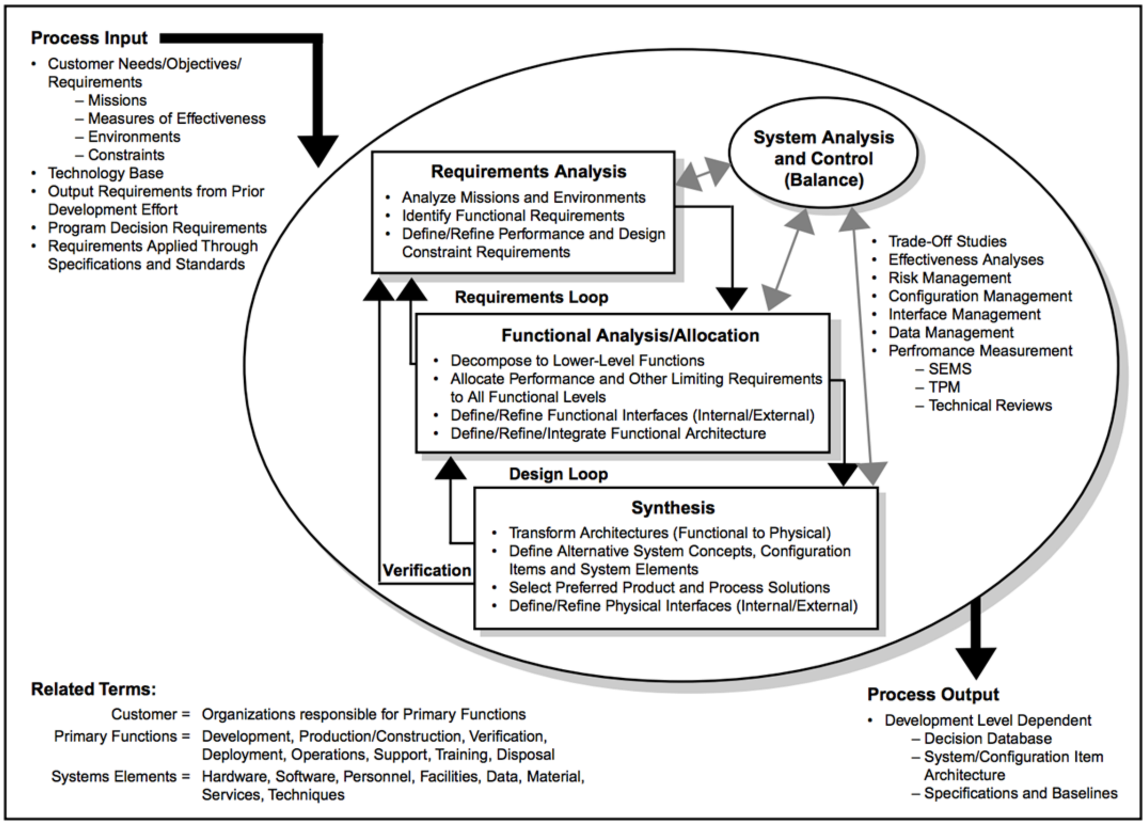

Figure 17. The Systems Engineering Process. Source: Systems Management College, Department of Defense (2001).

Figure 18 summarizes changes that were made to the DAU systems engineering process to adapt it to system of systems development. The process is similar; however, much of the functional analysis and synthesis becomes constrained by the characteristics of the constituent systems.

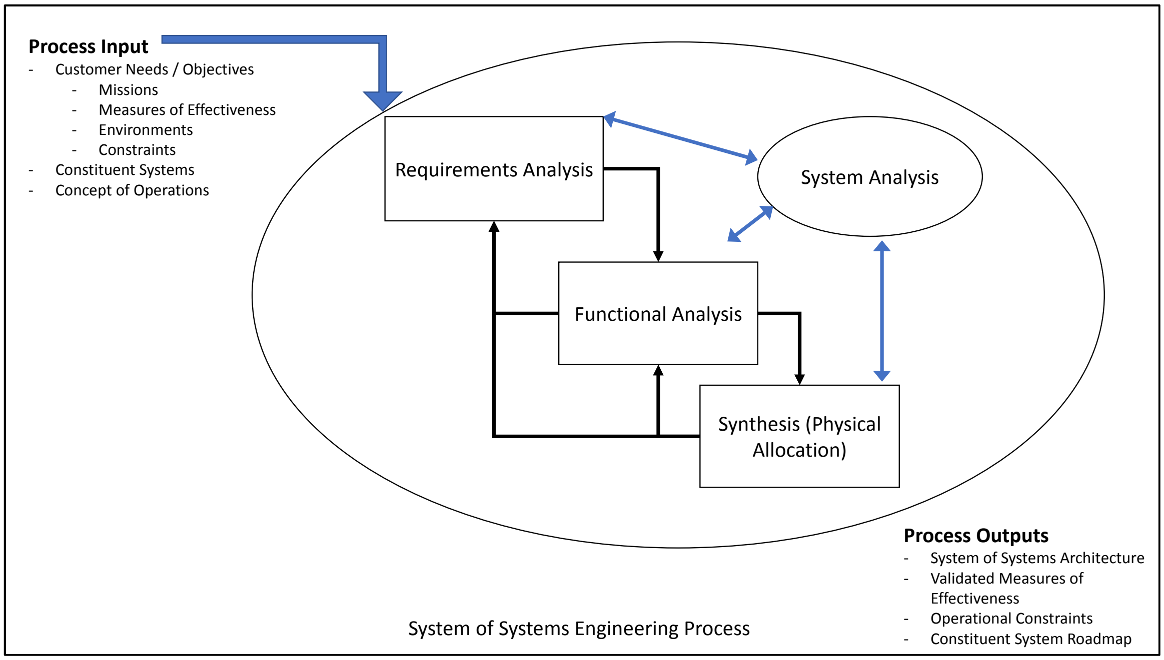

Figure 18. SOS Engineering Process. Source: Systems Management College, Department of Defense (2001).

The outputs from this modified system of systems development process are a proposed system of systems architecture; appropriate measures of effectiveness that can be used throughout the system of systems life cycle, operational constraints associated with system of systems employment, and a constituent systems roadmap to recommend improvements to constituent systems that would improve system of systems performance.

B. REQUIREMENTS ARCHITECTURE

The four key concepts of distributed lethality, developed in Chapter II.C, are the AFP; localized C3 within the AFP; a robust operations order; and assured communications with higher headquarters (typically a MOC). These assumptions form the basis for the requirements architecture for distributed lethality, shown in Figure 19.

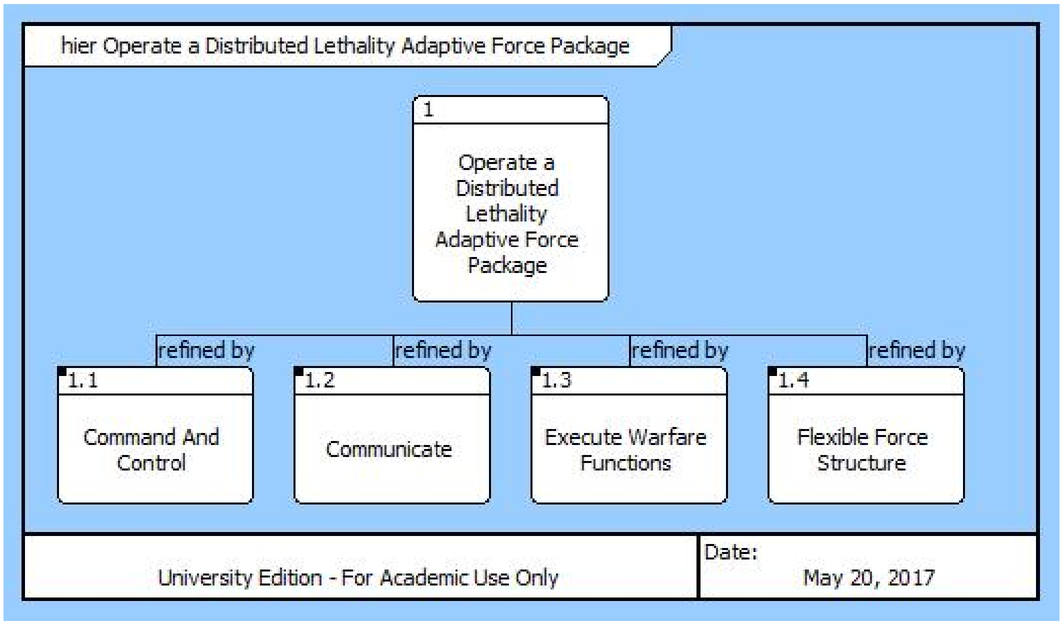

Figure 19. Top Level Requirements Diagram.

1. Command and Control Requirements

One of the key components of the AFP approach to distributed lethality is the delegation of many command decisions from the combatant commander (CCDR) to the AFP commander (CDR). This is in response to the high likelihood of the disruption of high-bandwidth satellite communications between the AFP and the CCDR. Much of the need for continuous communications between the AFP and the CCDR is reduced by a the CCDR issuing a well-defined OPORD prior to the beginning of a period in that a possibility exists of communications disruption, and the AFP CDR continuing to execute those operations until they are complete, or until conditions have changed to such an extent that extended communications between the AFP CDR and the CCDR are required.

As shown in Figure 20, the principle command relationships are between vessels in the AFP, the control retained by the CCDR, and the information contained in the OPORD.

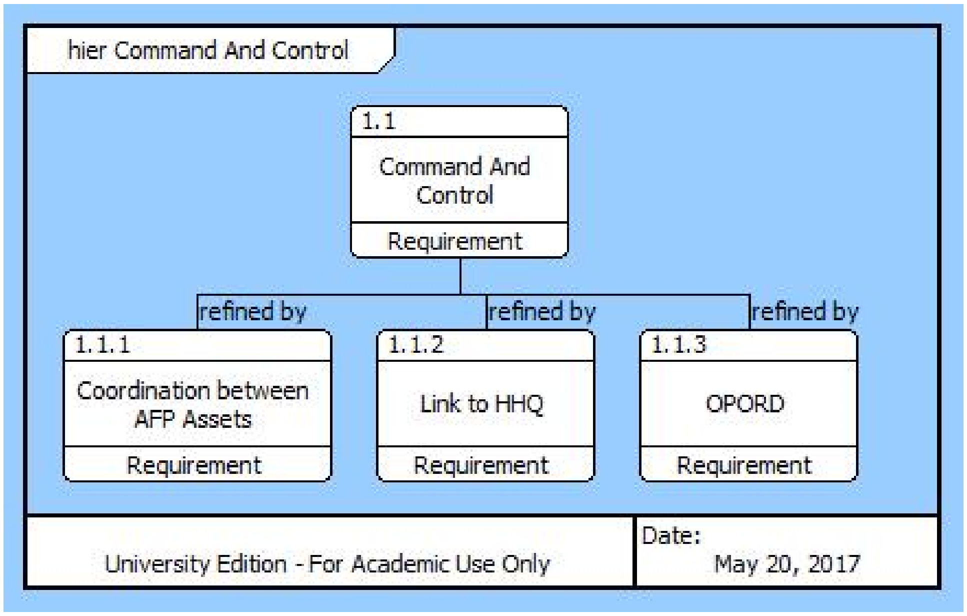

Figure 20. Command and Control Requirements.

Figure 21 describes the basic considerations that go into defining a distributed lethality OPORD. These characteristics map to those defined in Chapter II.B. The composition is flexible both based on available forces and the AFP mission, but can also be tailored via weapons loadout to address different threats. Designation of an operations area is important—distributed lethality missions should be confined both in geography and in duration to match the area that can be controlled by the weapons and sensors organic to the AFP, and to enable multiple AFPs to operate with reduced probability of friendly fire or overlapping sensor envelopes. By geographic planning, the CCDR can use multiple AFPs, each providing sea control over a designated geographic area, to achieve theater-level operational objectives. The rules of engagement designated for an AFP will need to extend beyond those used in the past, elaborating more on situations in that the AFP CDR can designate changes in sensor and weapons posture, and can, at their discretion, escalate or deescalate while keeping within pre-designated scenarios. Critical to this is establishing high-level criteria that will require the AFP to withdraw to a position where extended communications with the CCDR can take place to describe departures from the scenarios used to develop a particular OPORD. These may include things like unexpected adversary high value targets, degradation of a particular AFP capability, or a designated time. The communications plan defines channels and schedules; potentially this could involve long periods of the AFP operating under emissions control (EMCON) restrictions that permit breaking communications silence only when specific criteria in the rules of engagement (ROE) are met. Finally, the OPORD will delegate certain authorities to the AFP CDR beyond those that are typically spelled out in the ROE.

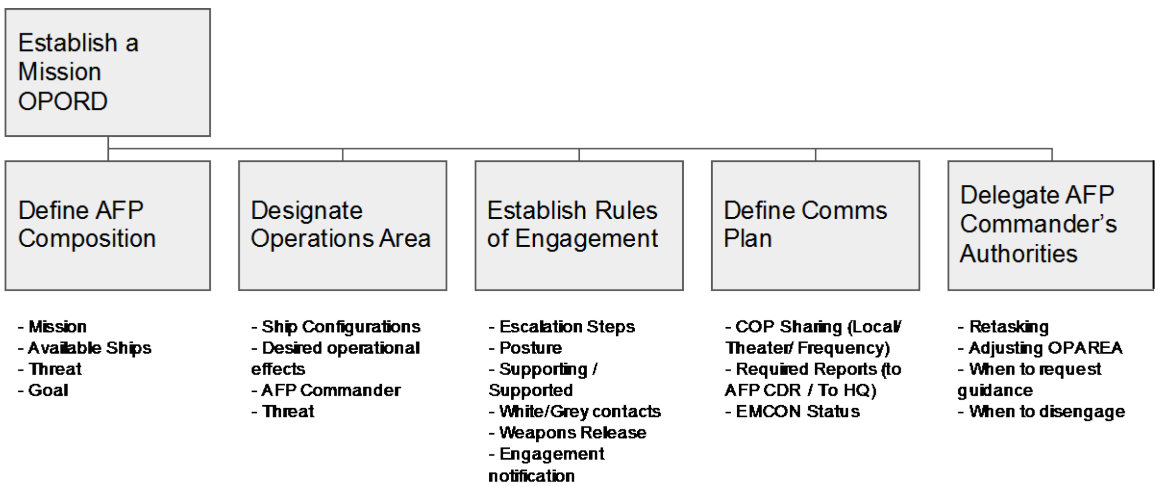

Figure 21. OPORD Considerations.

2. Communications Requirements

Two separate sets of communications requirements will need to be developed—a local datalink with high bandwidth and low probability of intercept/probability of detection characteristics to enable communications between AFP units, and a HHQ reach back circuit, with high-reliability, very low bandwidth characteristics. The distributed lethality CONOPS minimizes the communications necessary between the AFP and HHQ; however, when conditions deviate from the OPORD, it is critical that the AFP notify HHQ of the changes. Figure 22 shows the AFP communication requirements.

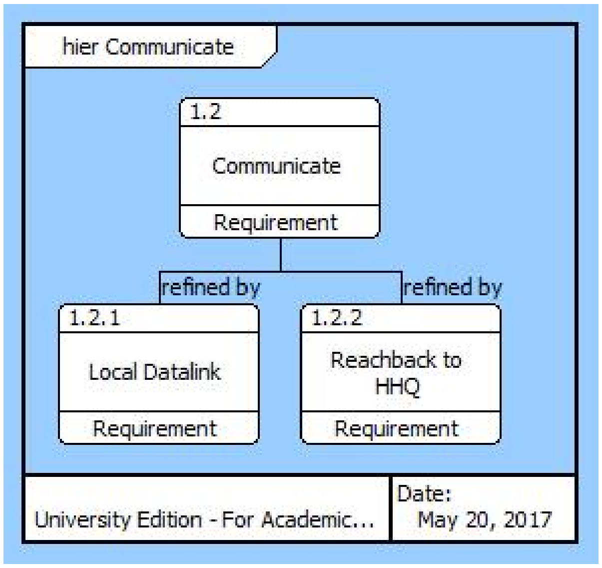

Figure 22. Communications Requirements.

3. Adaptive Force Package Mission Areas

The AFP construct exists in order to meet an offensive warfare need; as such, its primary focus is on being able to function as a cohesive unit. Mission areas are shown in Figure 23; as the focus of this report is on C2, no descriptions of these functions are provided.

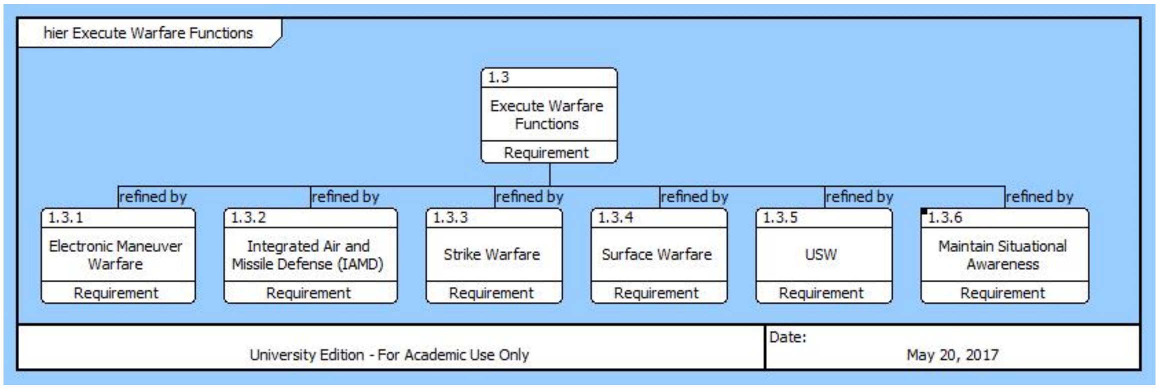

Figure 23. Adaptive Force Package Mission Areas.

4. Flexible Force Structure

The final set of requirements for the distributed lethality AFP is a flexible force structure. Third Offset Warfare (Hagel 2014), of which distributed lethality is the means for employment of naval forces in a third offset strategy, requires a force of capable and flexible officers, sailors, ships, aircraft, submarines, and unmanned vehicles. This is summarized by four requirements: Every platform a sensor; Every platform a communicator; Every platform a shooter; and Every platform a situational commander. This structure is shown in Figure 24.

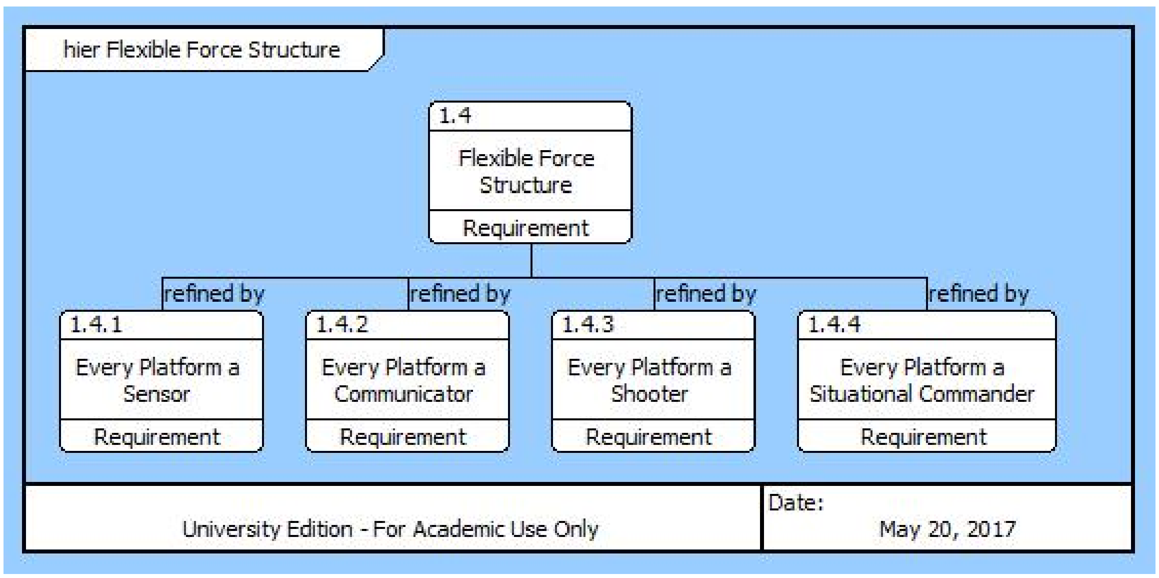

Figure 24. Flexible Force Structure Requirements.

"Every platform a sensor" establishes requirements that the AFP, when not operating in EMCON, share sensor-level data with other platforms in the AFP. This enables the development of cooperative sensing schemes, increasing the performance of legacy sensors. "Every platform a communicator" stops short of directly specifying a communications architecture; however, it does imply that every platform is able to participate as a node in the AFP intranet, and, if the ship has the physical footprint, every platform be able to provide the high-reliability datalink to HHQ. "Every platform a shooter" means that that all AFP platforms have offensive capability and that the platform(s) with the best solution to engage a hostile target may receive direction from the C2 structure to engage that target. Finally, "Every platform a situational commander" ensures that the best situated platform can be delegated at least some command function under the AFP construct, either based on capability, or as a planned deviation in the event that the AFP CDR can no longer participate on the network.

C. FUNCTIONAL FLOWS

This paper focuses on evaluating C2 structures for an AFP, and this chapter focuses on the functions necessary to develop and evaluate different C2 concepts for an AFP. One of the initial concerns while developing a functional architecture was a question of how to capture the control concept of delegation. This distributed lethality C2 study proposes capturing delegation and other control functions by treating the mission OPORD as a separate portion of the physical architecture. This provides several advantages: it provides a structure for capturing control decisions and evaluating different control architectures; it enables future integration of autonomous and semi-autonomous systems into the AFP architecture by providing a shared component between manned and unmanned platforms; and it provides a structure for force commanders to examine different mission constructs.

This distributed lethality C2 study does not examine all of the implications of this construction. The architecture change focuses on demonstrating improved command and control flexibility.

Figure 25 demonstrates the functional flow under an OPORD construct that reserves engagement authorities to higher headquarters (HHQ). A target is identified by an AFP unit. The unit follows guidance in the OPORD requiring all units to request weapons release authorization from higher command authority. This request is transmitted over the intra-AFP communications network. The AFP commander reviews the request against the OPORD, and refers the request to HHQ. HHQ reviews the request, and approves or rejects the weapons release request, which then has to flow back down the communications networks to the firing unit before the OASuW engagement can occur.

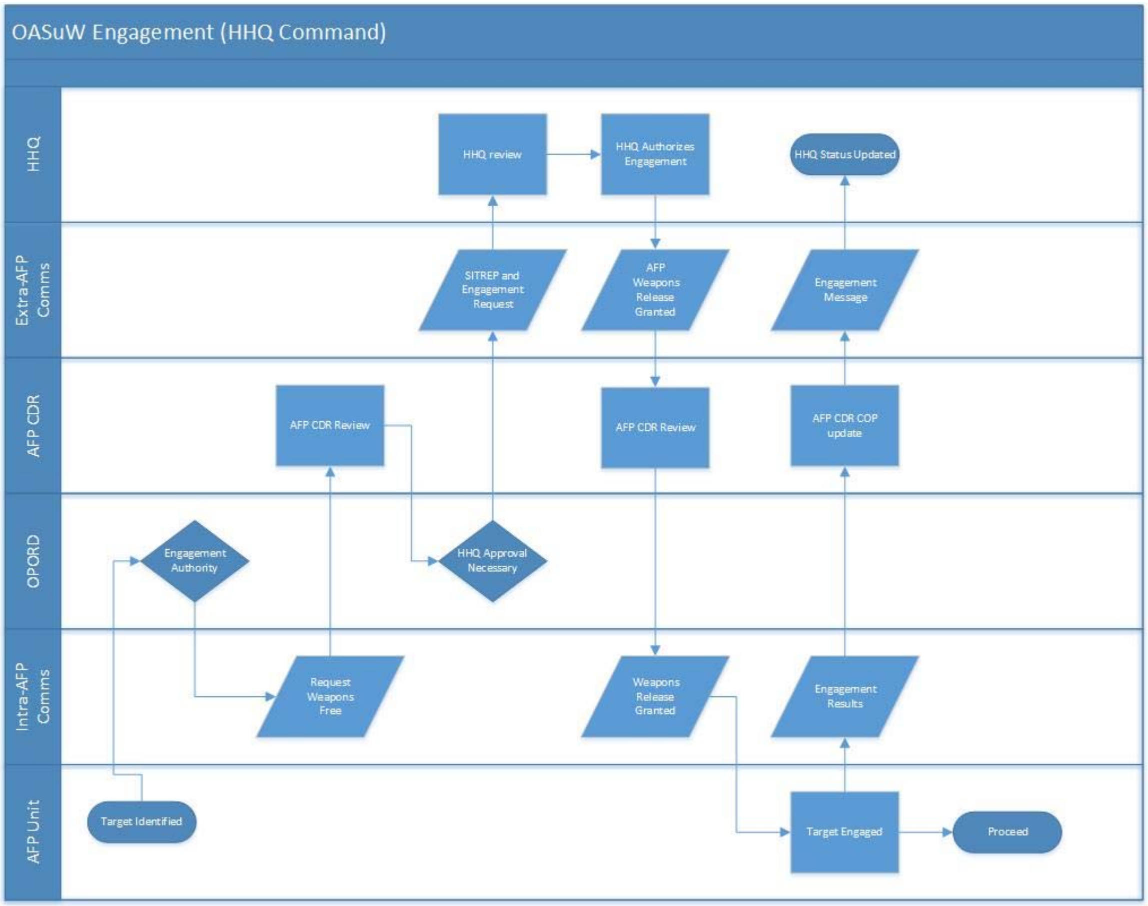

Figure 25. OASuW Engagement Functional Flow — Traditional C2.

When extra-AFP communications are robust, this decision-making cycle may be effective due to high-bandwidth reach back communications; however, in the event that communications are reduced, or in the case that multiple AFPs are requesting engagement authority, the delay associated with HHQ review may result in timelines that preclude successful OASuW engagements.

Contrast the functional flow in Figure 25 with that shown in Figure 26, in which the distributed lethality construct has delegated engagement authority to the AFP commander under conditions specified in the OPORD. In this case, the request to authorization cycle is reduced from 12 steps to eight steps, and both the long-latency communications step between the AFP and HHQ and the potential to overload the decision-making capability of HHQ is avoided in the second construct.

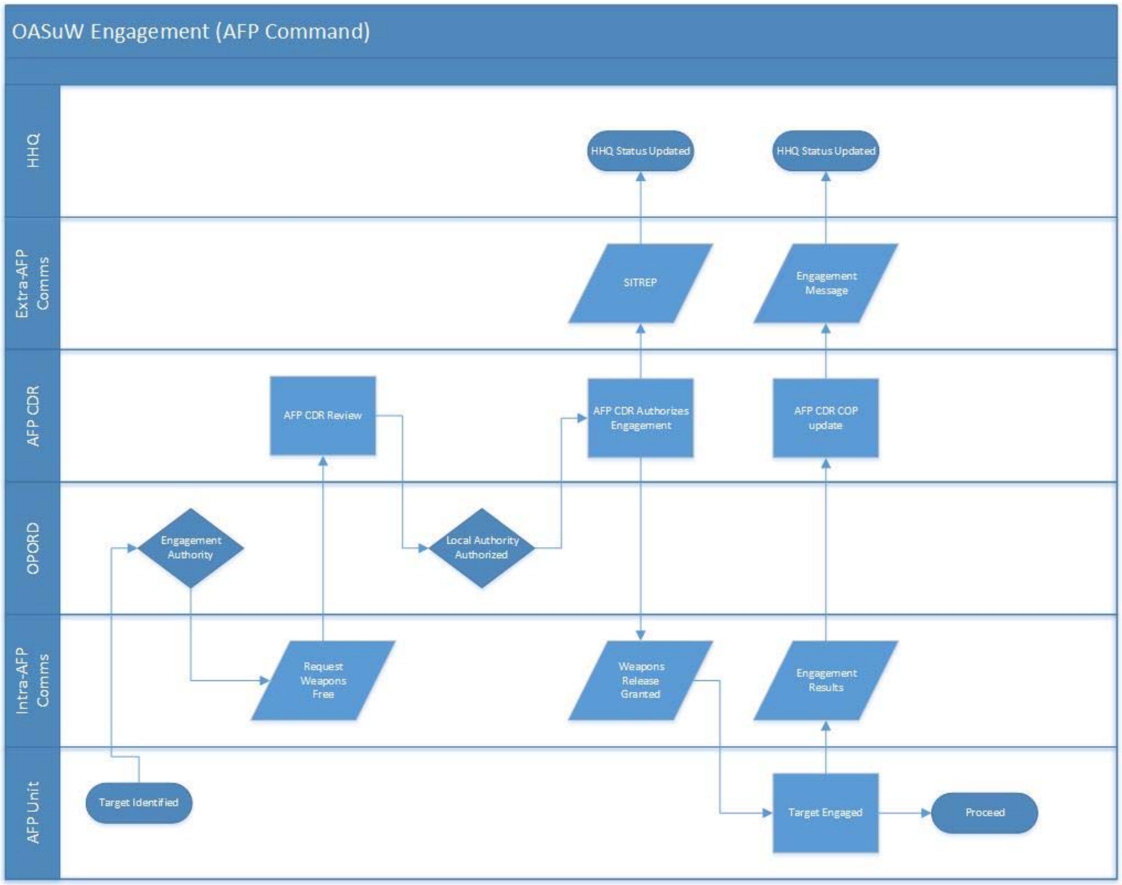

Figure 26. OASuW Engagement Functional Flow — Distributed Lethality C2.

D. FUNCTIONAL DECOMPOSITION

A general functional decomposition for surface warfare over the horizon engagements was proposed in "Organic Over-The-Horizon Targeting for the 2025 Surface Fleet" (Johnson et al. 2015). The architecture is shown in Figure 27.

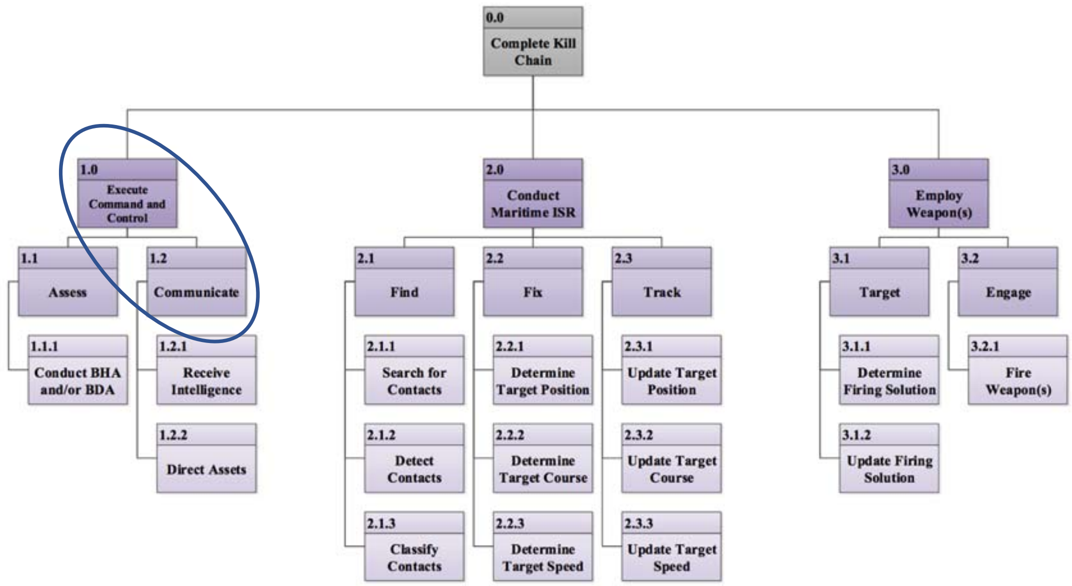

Figure 27. Organic OTHT Surface-to-Surface Functional Decomposition. Source: Johnson et al. (2015).

The AFP construct in this distributed lethality C2 study continues to employ branches 2.0 "Conduct Maritime ISR" and 3.0 "Employ Weapon(s)"; however, in this study we propose an alternative functional architecture for 1.0 "Execute Command and Control," as expanded upon in the following paragraphs.

The alternate functional architecture described in Figure 28 forms the basis of the systems analysis chapter of this report. Referring to the architecture in Figure 27, Function 1.0 is broken into a command function and a control function, and Function 1.2 is elevated to a first level communicate function. This new structure allows for system analysis of a change in command structure, through the assignment of different decision points to simulate changes to the OPORD, and the evaluation of different communications architectures for the communicate function. The performance of competing command, control, and communications systems are assessed in detail in Chapter IV, with a description of metrics associated with those top-level functions.

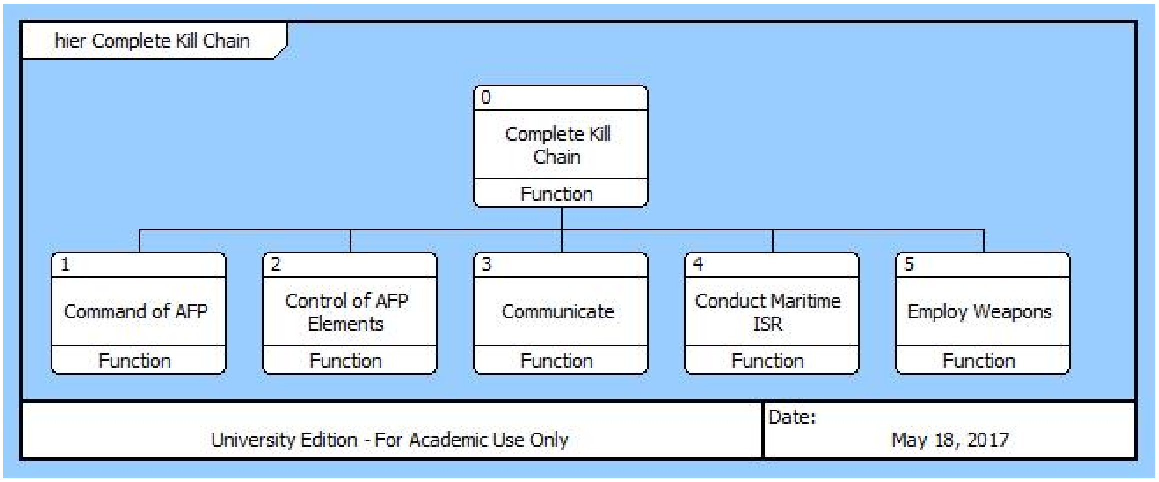

Figure 28. Revised Functional Hierarchy.

To the functional architecture proposed in (Johnson et al. 2015), this study divides the first element into three elements to enhance distributed lethality C2:

1. The "Command of AFP" function designates both the operational and tactical command functions associated with distributed lethality. Command functions are the class of functions associated with evaluating information and making decisions.

2. The "Control of AFP Elements" function is associated with assignment of specific tasks to specific units of the AFP. Control functions are the class of functions that involve moving physical objects, changing operations modes for sensors, and establishing communications states (EMCON or other postures).

3. The "Communicate" function is associated with sharing information and reports with higher headquarters and other units in the AFP.

This decomposition allows for more granular definition of functions and the distribution of functions across the AFP to a level that lets sensors, weapons, and control be shared across the AFP. One possible end-state of this architecture allows for the AFP commander embarked on one vessel to engage an enemy target sensed on a second vessel or another AFP asset with a weapon from a third party.

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IV. PHYSICAL ARCHITECTURE

A. DISTRIBUTED LETHALITY PHYSICAL ARCHITECTURE

Distributed lethality doctrine is developing and subject to change as operational experience matures and technologies evolve. The C2 physical architecture for distributed lethality is based upon adaptations to current U.S. Navy C2 doctrine, communication and warfare systems. This architecture follows the distributed lethality characteristic of using current or near future technologies.

B. PHYSICAL ARCHITECTURE COMPONENTS

While this study focuses primarily on the evaluation of command, control, and communications architectures for distributed lethality, it also establishes a physical architecture for the distributed lethality system of systems. At its highest level, the distributed lethality force construct can be broken down into four architecture components: headquarters, networks, an operations order, and the adaptive force package. Figure 29 shows this architecture.

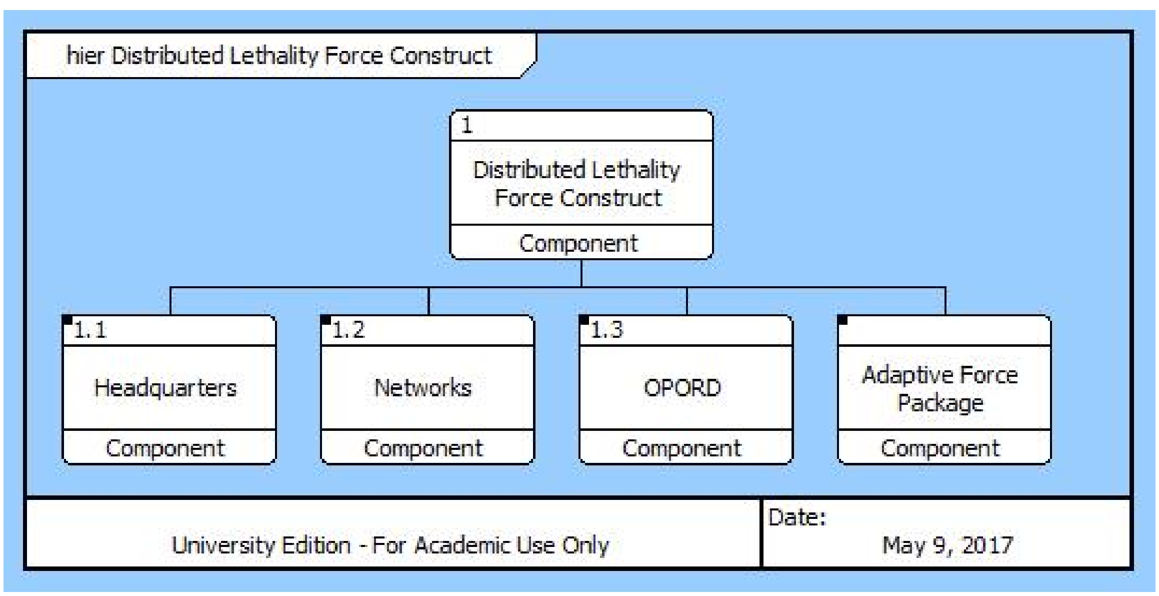

Figure 29. Distributed Lethality Physical Architecture.

This is an expansion of typical physical architecture, in that it includes both the personnel in the headquarters component and the data and processes documented in the OPORD component. The INCOSE definition of physical architecture allows that, "A system element is a discrete part of a system that can be implemented to fulfill design properties. A system element can be hardware, software, data, humans, processes (e.g., processes that provide a service to users), procedures (e.g., operator instructions), facilities, materials, and naturally occurring entities (e.g., water, organisms, and minerals), or any combination of these ISO/IEC/IEEE 15288 (ISO 2015)" (SEBoK authors 2017).

1. Headquarters

The distributed lethality headquarters is typically the numbered fleet MOC assigned to a GCC, serving as the maritime component commander (MCC). Below the headquarters component, there are four sub-components: Extra-AFP relationships, a force allocation, a link to higher headquarters (HHQ)/fleet/regional combatant commander (RCC), and a set of tasking priorities. Figure 30 shows this architecture.

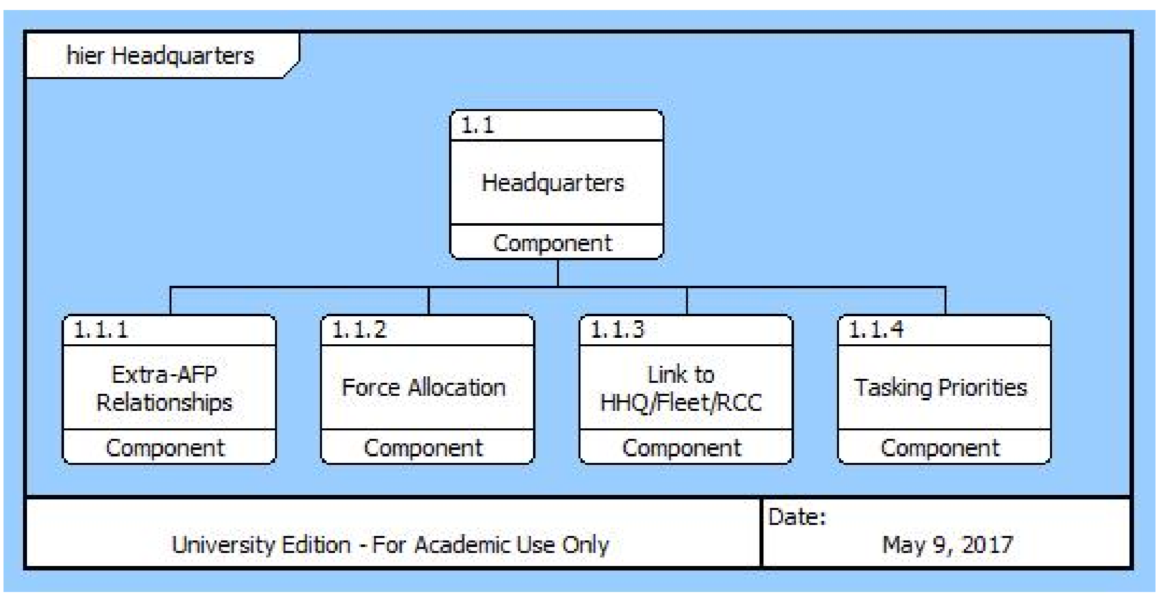

Figure 30. Distributed Lethality Headquarters Physical Architecture.

The “Extra-AFP Relationships” component in Figure 30 are interfaces to other units operating in and out of theater, including other components of the Department of Defense, national assets, and allies. “Force Allocation” component in Figure 30 are the forces available to the HHQ from which an AFP can be drawn. “Link to HHQ/Fleet/RCC” component in Figure 30 is the processes through which a HHQ coordinates AFP tasking with other component commanders. “Tasking Priorities” component in Figure 30 is the process through which HHQ develops priorities that are fed to the AFP commander via the OPORD.

2. Networks

In general, there are two distinct sets of communication networks required for the operation of an AFP. Extra-AFP communications are the systems through which the AFP commander interfaces with HHQ and other participants in the GCC area of responsibility. Intra-AFP communications permit AFP platform coordination during execution of the AFP OPORD. These components are shown in Figure 31.

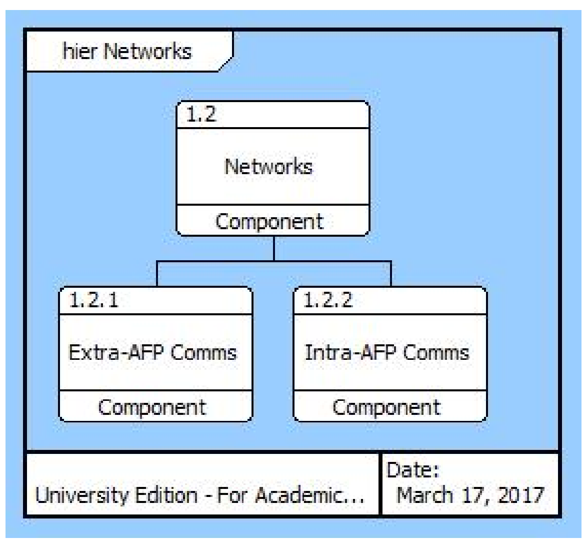

Figure 31. Distributed Lethality Network Physical Architecture.

Extra-AFP communications are a family of systems characterized by high reliability systems optimized for operation in contested spectrum environments. Extra-AFP communications are detailed in the concept of operations. While this study does not detail or allocate requirements to specific systems, some existing systems operating in the high frequency (HF) through extremely high frequency (EHF) bands may currently meet the requirements.

Intra-AFP communications are critical to the AFP C2 concept developed in this study because they are the backbone for information exchange and sensor networking.

a. Intra-AFP Communications

Intra-AFP communications components are tactical data links onboard on all platforms participating in the AFP. This study does not assign a specific tactical data link to perform C2 data transport. The data link is simply the transport medium to be selected based upon communication range and other desired properties discussed in Chapter II.D. The tactical data link for the intra-AFP communications system is assumed to be a multi-user networked system that is interoperable with USN, joint, and coalition forces that are components of the AFP.

Three communications network architectures are modeled for physical architecture comparisons: centralized, decentralized, and distributed. The network architectures of a five platform AFP are illustrated in Figure 32, Figure 33, and Figure 34.

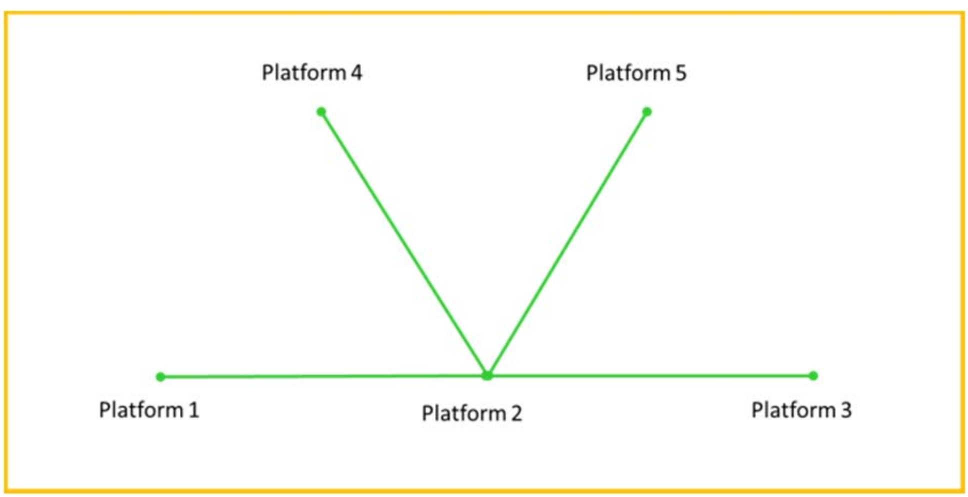

Figure 32. Centralized C2 Network Architecture.

In the centralized C2 network architecture of Figure 32, platform two is the central node. No redundant communication transport paths exist. Loss of the node at platform two breaks the intra-AFP communications network. Under this network, any platform may be the AFP commander. Transport cost when platform two is AFP commander is a single hop for point-to-point waveform communications or two hops when airborne relays are required to bridge the distance between platforms. Transport cost when any platform other than platform two is AFP commander is two hops for point-to-point waveform communications or four hops when airborne relays are required.

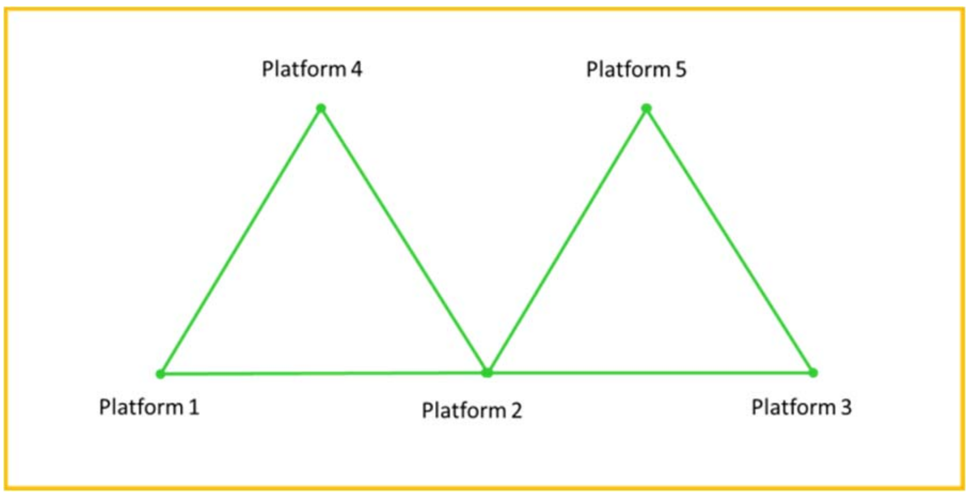

Figure 33. Decentralized C2 Network Architecture.

In the decentralized C2 network architecture of Figure 33, platform two is the central node connecting all platforms into a single decentralized network. Multiple redundant communication transport paths exist. Loss of one path to any node does not severely degrade the intra-AFP communications network. Loss of any node, other than two, only affects the lost node. Loss of the node at platform two splits the network into two separated networks. Under this network, any platform may be the AFP commander.

The decentralized network physical architecture should include a smart command and control processor (C2P) to route messages via the fastest available transport path. Network protocols and C2 messaging design should accommodate multiple copies of redundant transmissions when routing messages. A five-node decentralized communications network could result in one original C2 message and three duplicate copies of the original message.

For example, platform one addresses a C2 message to platform three and transmits the message via both available paths to platform two and four (without smart C2P). Platform two forwards the message via both available paths to platform three and five. Platform three receives the original message at the same time platform five receives the duplicate message from platform two. Platform five forwards the duplicate message to platform three. Simultaneously, platform two receives a duplicate of the original message from platform four and forwards two copies to platform three and five, resulting in platform three receiving the original C2 message and three duplicate copies.

Network routing is beyond the scope of this study. Network routing is highlighted here as a need for additional study to optimize network design with smart network C2P routing that minimizes copies of message traffic, minimizes transport time/costs, and provides a robust message processing design in the event of duplicate messages. A smart C2P architecture would sense the network routing paths and route the C2 message only from platform one to two to three. A secondary benefit of smart routing is a reduction in RF radiations by eliminating redundant transmissions by AFP platforms.

Transport cost when platform two is AFP commander is a single hop for point-to-point waveform communications or two hops when airborne relays are required. Transport cost when any platform other than platform two is AFP commander is two to four hops for point-to-point waveform communications or four hops when airborne relays are required.

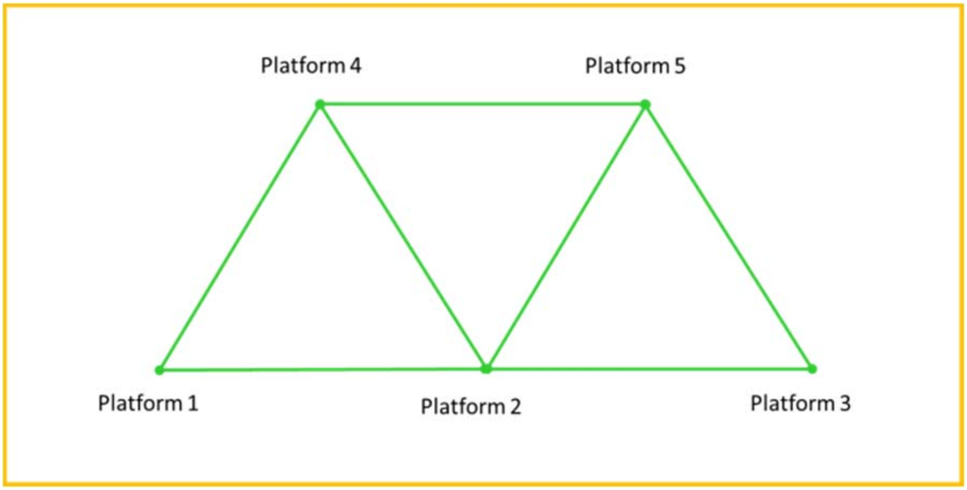

Figure 34. Distributed C2 Network Architecture.

In the distributed C2 network architecture of Figure 34, no central node exists. The maximum number of redundant communication transport paths exist. Loss of a single path to any node does not severely degrade the intra-AFP communications network. Loss of any node only affects the lost node. Under this network, any platform may be the AFP commander. The distributed network should employ smart C2P routing to function via fastest transport path and provide a robust message processing design in the event of duplicate messages. Transport cost when platform two is AFP commander is a single hop for point-to-point waveform communications or two hops when airborne relays are required. Transport cost when any platform other than platform two is AFP commander is two to four hops for point-to-point waveform communications or four hops when airborne relays are required.

3. Operation Order

The OPORD is the ruleset that establishes parameters under which the AFP is required to operate. While OPORDs have been used in military operations for decades, this study moves the definition of the AFP OPORD into the SOS physical architecture. This placement in the physical architecture is critical for determining the characteristics of the communications between the AFP and HHQ (extra-AFP communications, discussed in the previous chapter), and in setting parameters for the functional analysis of the AFP. The components of the OPORD considered in this study are shown in Figure 35.

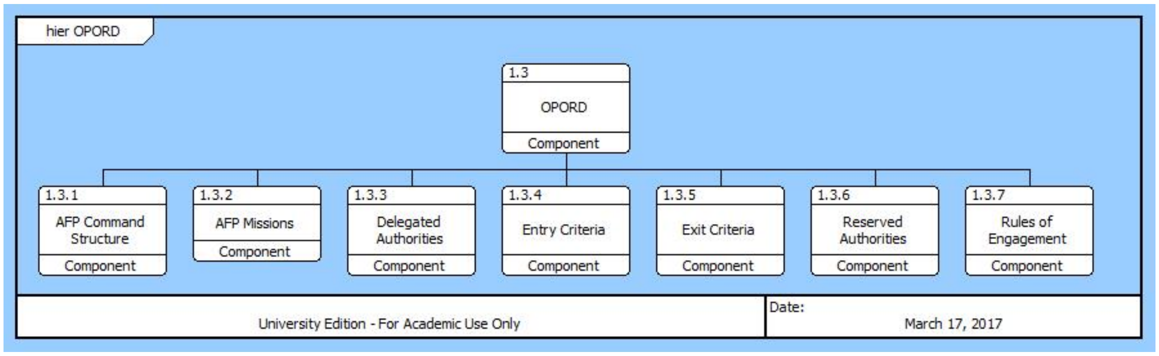

Figure 35. OPORD Physical Architecture.

The "AFP Command Structure" component in Figure 35 designates the unit that will serve as the AFP commander and may designate other roles specifically to other AFP platforms. Assignment of this structure is normally at the discretion of the AFP commander.

The "AFP Missions" component in Figure 35 are the specific goals assigned to the AFP. HHQ coordinates tasking priorities with other force providers supporting the GCC, and the AFP missions are a combination of supported tasking, in which the AFP is the lead in completing the mission, and supporting tasking, in which the AFP is providing the capability to another force supporting the GCC.

The "Delegated Authorities" component in Figure 35 defines what decisions are to be made or delegated by the AFP commander. The System Analysis in Chapter V of this report examines the delays and communication overhead incurred when all decisions must be made at a level above the AFP commander; this study demonstrates the operational flexibility and autonomy gained by pushing decisions forward even as the communications environment becomes contentious.

The entry and exit criteria components in Figure 35 define conditions that change the roles and permissions under which the AFP commander operates. A simple example of this would be a time window around an OASuW mission: "At 0800, engage all surface combatants from (a country) positively identified with a (sufficient) track quality. Engagement will continue until 1200, or until 30% of (OASuW weapons) are expended."

The "Reserved Authorities" component in Figure 35 are tasks or conditions under which the AFP commander MUST contact HHQ before proceeding.

4. AFP Units

The AFP may consist of any mix of the family of systems shown in Figure 36. The AFP component construct allows for operational flexibility depending upon the platforms available to HHQ. The AFP model in the physical architecture of this study consists of two DDGs and three LCS. A physical architecture with five platforms permits modeling the three network types under study. Other platforms may join the architecture as mission requirements and platform availability dictate. The distributed lethality AFP architecture can be extended to include any interoperable platform capable of participating in the intra-AFP communications network.

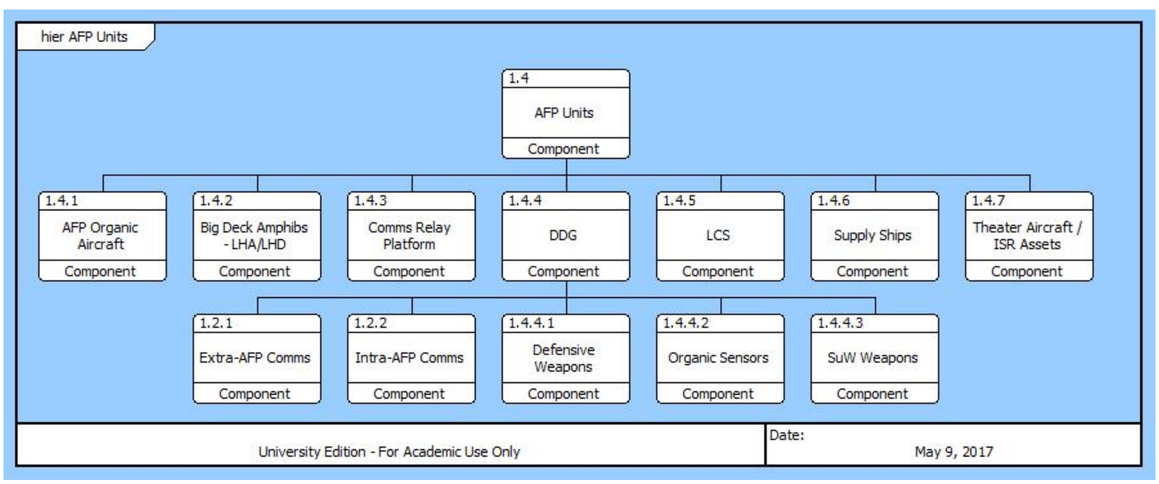

Figure 36. AFP Units.

Figure 36 includes a second level of physical decomposition to show the typical physical systems required for a platform to be used as an AFP unit. The distributed lethality construct developed by this study includes both offensive and defensive weapons capabilities on each platform; "If it floats, it fights" (Rowden 2016).

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V. SYSTEM ANALYSIS

A. SIMULATION DESCRIPTION

The distributed lethality physical architecture model and simulation results in this chapter are built using ExtendSim version 9.2 software program (Imagine That 2015). The simulation is based on the South China Sea wargame scenario described in Chapter II.D. The simulation models C2 message transmission and reception across a five platform AFP. Modeling and simulation provides an understanding of the C2 message behavior based on simulation parameters and network physical architectures. Several test cases are evaluated in Chapter V.B to maximize network performance and draw recommendation and conclusions. The simulation model for this simulation is new with no external peer review or model validation outside of the analysis performed by the modeling team.

1. Block Diagram

The ExtendSim simulation is built following the block diagram in Figure 37. This block diagram is based upon Figure 25 and Figure 26 in functional flows described in Chapter III.

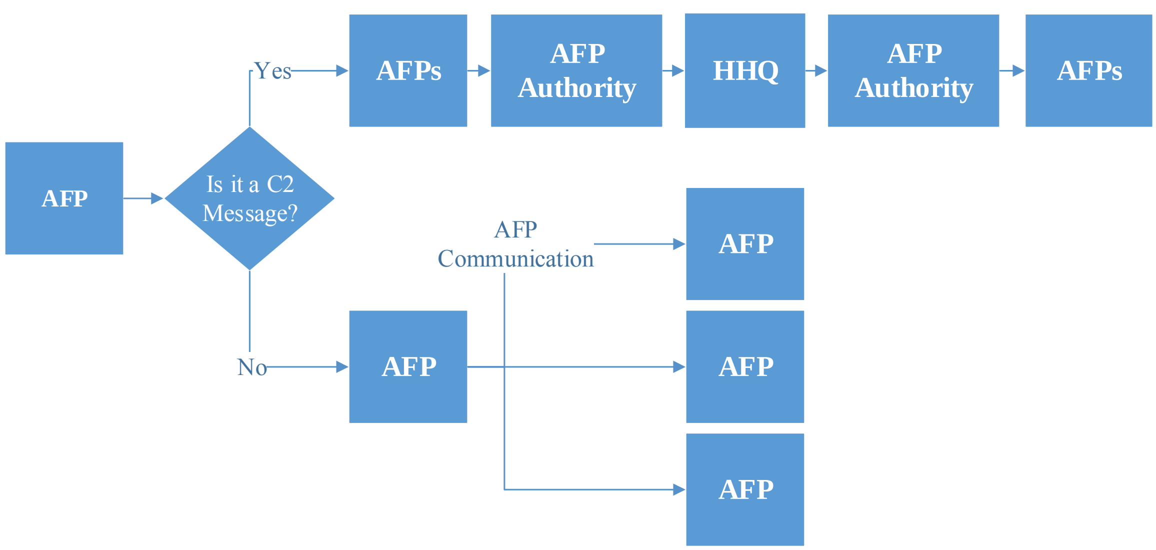

Figure 37. Simulation Block Diagram.

The block diagram emulates C2 communications for a single AFP with five platforms. The communication flow in Figure 37 shows the message path from one node to any other node. It demonstrates two categories of messages the AFP exchanges and the process cycle for each message type. The messages categories are: C2 messages and non-C2 messages. This architecture defines C2 messages as messages sent by a commander to a subordinate platform directing mission assignment, engagement or weapons control, and the corresponding response from the platform. Non-C2 messages are all other platform-to-platform data exchanges within the AFP, including situational awareness data or other information not related to C2. Non-C2 message transfer within the AFP occurs at a lower transmission priority than C2 messages and may flow through the AFP over the same tactical data link used for C2. The AFP commander may route the C2 message to HHQ if a C2 network connection exists. C2 message replies from HHQ flow back to the AFP platform that originated the C2 message.

2. Parameters

Parameters for C2 network simulations are approximations of anticipated network transport times and are the primary input variables for all simulations. C2 message parameters for the simulation are shown Table 2. The simulation models timing parameters for transmission and reception of C2 messages. Message transmit processing time is the time that it takes the AFP platform to transmit a C2 message to the network from initiation of an operator or automatic message transmit request. Message receive processing time is the time the AFP platform or HHQ receives the message from the C2 network, the message is reviewed by human operators, and a response is available for transmission back to the originator of the C2 message. The parameters are given a normal distribution or a triangular distribution to simulate variations in network and human response times. C2 message receive processing time within the AFP and HHQ have a triangular distribution because the C2 messages require human approval for items such as operation orders and HHQ input. The minimum, maximum and most likely values in the triangular distributions are rounded estimates from the research team based on their professional experiences. The mean and standard deviations in the normal distributions are estimated values.

Table 2. C2 Message Parameters

Parameters	Distribution	Values
Message Transmit Processing Time	Normal	Mean = 1.5 seconds Standard Deviation = 0.15 seconds
Message Receive Processing Time AFP C2 Message	Triangular	Minimum = 1 minute Most likely = 2 minutes Maximum = 5 minutes
Message Receive Processing Time HHQ C2 Message	Triangular	Minimum = 5 minutes Most likely = 15 minutes Maximum = 30 minutes

Non-C2 messages are all other platform-to-platform data exchanges within the AFP, including situational awareness data or other information not related to C2. The simulation models non-C2 message transmission and reception between AFP platforms. Non-C2 message timing parameters are shown in Table 3.

Table 3. Non-C2 Message Parameters

Parameters	Distribution	Values
Message Transmit Processing Time	Normal	Mean = 100 milliseconds Standard Deviation = 10 milliseconds
Message Receive Processing Time Non-C2 Message	Normal	Mean = 100 milliseconds Standard Deviation = 10 milliseconds

Table 4 lists general message or environmental parameters used by the simulation. Message transmit rates specify the frequency non-C2 messages are repeated by a single AFP platform. Message dropout rate is the probable message loss rate during transmission due to environmental spectrum effects or interference. The C2 message percentage is the percentage of all messages being produced by a single AFP platform that are high priority C2 messages.

Table 4. General Parameters

Parameters	Values
Message Transmit Rate	12 seconds
Message Dropout Rate	10%
C2 Message Percentage	5%

3. Metrics

a. Measure of Effectiveness

The NAVSURFOR liaison to the Naval Postgraduate School recommended that the distributed lethality C2 research team use "missile-off-the-rail" as a basis for MOE. The distributed lethality C2 team refined this guidance to use time from detection until the time of engagement of a threat—MOE 3: C2 Message Cycle—as the primary operational MOE. These MOEs were further developed into Measures of Performance (MOP) for the scenario and simulation. The MOEs and MOPs are traced to functions in Figure 27, Figure 28 and Table 5.

Table 5. MOE/MOP

Function	Measure of Effectiveness	Measure of Performance
1.2 Communicate	MOE 1: Message Transmission Success Rate	MOP 1.1: C2 Message Success Percentage
		MOP 1.2: Non C2 Message Success Percentage
	MOE 2: Message Delivery Time	MOP 2.1: C2 Message Delivery Time
		MOP 2.2: Non-C2 Message Delivery Time
1.2.1 Receive Intelligence	MOE 3: C2 Message Cycle	MOP 3.1: Time to Engage from Request
1.2.2 Direct Assets		

b. Simulation Metrics

Simulation metrics are based upon stakeholder inputs, which were turned into MOE and MOPs in Table 5 and are collected as outputs of simulation runs for each case. The metrics are then fed into post-simulation data evaluation. The metrics are:

- Message Delivery Success Rate: This metric reports the percentage of messages delivered successfully for C2 messages and the non-C2 messages.

- Message Mean Time to Delivery: This metric reports the mean time to deliver C2 messages and non-C2 messages.

- Time to Engage from Request: This metric reports the amount of time it takes a message to complete the C2 processing cycle.

4. Assumptions/Constraints

The selected assumptions and constraints describe the simulation set boundaries. The simulation contains the following assumptions and constraints:

- The simulation begins when an AFP platform generates a C2 request and ends when that platform receives a decision from the commander.
- The simulation is a 24-hour scenario resulting in approximately 7200 messages per run.
- The AFP platforms only send a given message once; there are no retransmissions based on failed message delivery. While retransmissions are common in networks, this is a reasonable assumption for this simulation because this simulation is looking at message paths, which are the same for single transmissions or multiple transmissions.
- The dropout rate is the same for every communication link in the simulation.
- The dropout rate does not vary with transmission distance.

B. TEST CASES

The test cases investigate C2 architectural behaviors based upon the parameters established in Chapter V.A.2. The cases compare C2 networking architecture and AFP platform effectiveness. The following test cases are analyzed:

- Test Case 1: Network Architecture
- Test Case 2: AFP Commander
- Test Case 3: Jamming Environment
- Test Case 4: Command Decisions

In each test case, the output metrics from Chapter V.A.3 are compared between the independent variables. Statistical testing is used to determine statistical significance. The statistical tests are two sample t-tests assuming unequal variances and paired t-tests when appropriate. The level of significance used is $\alpha = 0.05$.

1. Test Case 1: Network Architecture

This test case compares the three types of network architectures (centralized, decentralized, and distributed). Test case 1 holds all the parameters constant with the only variant factor being the network architecture types. The results of ten simulation runs for each network type (centralized, decentralized, and distributed) are summarized in Table 6 to show the collected mean output data for each of the network architectures.

Table 6. Network Architecture Comparison

Network	Mean Message Delivery Time (Seconds)		Message Delivery Success		Time from Request to Engagement (minutes)
	Non-C2 Messages	C2 Messages	Non-C2 Messages	C2 Messages	
Centralized	0.20	130.18	90%	68%	21.49
Decentralized	0.20	130.00	90%	79%	21.25
Distributed	0.20	130.85	90%	80%	21.02

The results are as expected for the given network types. The distributed network was expected to have the highest success rate for C2 messages delivery because of multiple redundant communication paths for each platform in the AFP. The decentralized network performs almost as efficient as the distributed network because it contains similar communication paths. The centralized network has no redundant paths for the platforms and has the lowest C2 messages delivery success rate.

A two-sample t-test is performed to determine the key metrics and compare the network architecture effectiveness between each other. The simulation output data for all Table 6 test cases is located in Table A-1 of Appendix A, and the t-test analysis is available in Table C-1 of Appendix C. Based on the P-values shown in Table 7 and Table 8, we can conclude the C2 message delivery success percentage, and time from request to engagement metrics are statistically significant between the network architectures. As a result, it can be determined that the distributed network architecture performs the best followed closely by decentralized networks. Centralized networks have the lowest performance. This analysis supports our expectations that distributed networks perform the best based on our metrics. In addition, the difference between time from request to engage may only be 28 seconds, but even a small amount of time can have an impact on operational effectiveness.

Table 7. C2 Message Delivery Success P-Value

C2 Delivery Success	
Alternative Hypothesis	P-value
Distributed > Centralized	1.91E-14
Distributed > Decentralized	0.0009
Decentralized > Centralized	1.09E-12

Table 8. Time from Request to Engagement P-Value

Time from Request to Engagement	
Alternative Hypothesis	P-value
Distributed > Centralized	9.50E-07
Distributed > Decentralized	0.0024
Decentralized > Centralized	0.004

2. Test Case 2: AFP Commander

Test case 2 varies which AFP platform performs single point C2 message forwarding from within the AFP to HHQ to simulate a case where satellite communications are available to a single AFP platform, as illustrated in the OV-1 AFP Concept of Operations. This case is important from an operational viewpoint because it indicates the best platforms to forward C2 messages dependent upon network topology and recommends geometry of the AFP. The simulations ran ten times for each platform as a C2 message forwarder. The distributed network is chosen for all simulations and all other parameters are kept constant. The simulation results for this test case are shown in Table 9.

Table 9. AFP Platform as C2 Forwarder

AFP Platform	Mean Message Delivery Time (Seconds)		Message Delivery Success		Time from Request to Engagement (minutes)
	Non-C2 Messages	C2 Messages	Non-C2 Messages	C2 Messages	
LCS 1	0.20	130.01	90%	80%	21.02
LCS 2	0.20	130.85	90%	80%	21.02
LCS 3	0.20	130.26	90%	80%	20.98
DDG 1	0.20	130.08	90%	81%	21.00
DDG 2	0.20	130.54	90%	80%	21.03

The results show the system is indifferent with respect to which AFP platform is the C2 message forwarder. This is consistent with our rationale that it should not matter which platform is forwarding C2 messages to HHQ.

A two-sample t-test is performed for this test case. The simulation output data for all Table 9 test cases is located in Table A-2 of Appendix A, and the t-test analysis is available in Table C-2 of Appendix C. Based on the two sample test analysis results, there are no statistical differences on which AFP platform forwards the C2 message to HHQ.

3. Test Case 3: Simulated Contested Spectrum Environment

This test case focuses on the network architecture performance under a simulated contested spectrum environment between the AFP platforms nodes. For this test case, the C2 message dropout rate parameter was changed to a uniform distribution that varies from zero to 100. Fifty random samples were chosen from the distribution and used for each network type. Each sample was used as an input parameter for a single run. Therefore, the simulations were run 50 times for each network type. All the other simulation parameters remained constant. The message dropout rate network architecture results are in Figure 38.

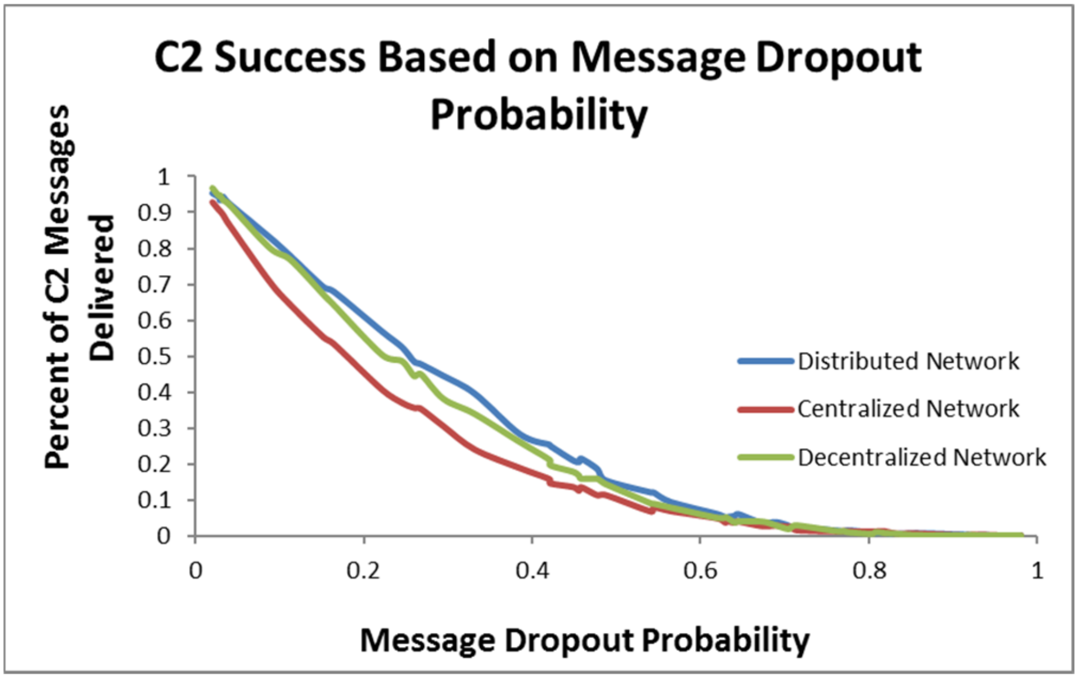

Figure 38. C2 Success in Simulated Contested Spectrum Environment.

Figure 38 illustrates that message dropout probability has a significant impact on C2 delivery success. To compare the networks, a paired t-test analysis was performed for this test case because each network type had the same input parameters. The simulation output data for Figure 38 test cases is located in Table A-3 of Appendix A, and the t-test analysis is available in Table C-3 of Appendix C. Based on the P-values in Table 10, we can conclude the C2 message delivery time and time from request to engagement metrics are statistically significant between the network architectures. As a result, it can be determined that the distributed network architecture performs the best followed closely by decentralized networks. Centralized networks have the lowest performance.

Table 10. C2 Success Rate Paired T-Test

Alternative Hypothesis	P-value
Distributed > Centralized	3.49E-08
Distributed > Decentralized	8.50E-07
Centralized < Decentralized	1.55E-07

4. Test Case 4: Command Decisions

This test case analyzes the effects of changing the command authority level and its ability to exchange C2 messages in a simulated contested spectrum environment. The test case changes the command authority from HHQ to the AFP commander and looks at the impact of this change to the C2 message dropout rate. Test case 4 executed two separate runs. In the first run, all parameters were constant with the only variant factor being the decision authority. The simulations ran ten times for each authority type. In the second run, the C2 message dropout rate parameter was altered by changing it to a uniform distribution with variance from zero to 100%. Fifty random samples were chosen from the distribution and used for each command authority. Each sample was used as an input parameter for a single run. Therefore, the simulations were run 50 times for each command authority. The distributed network architecture is employed and all other simulation parameters remained constant. The output simulation results for the command authority are shown in Table 11 and Figure 39.

Table 11. Command Authority Levels

Command Authority	Mean Message Delivery Time (Seconds)		Message Delivery Success		Time from Request to Engagement (minutes)
	Non-C2 Messages	C2 Messages	Non-C2 Messages	C2 Messages	
AFP Platform	0.20	130.46	90%	90%	4.34
HHQ	0.20	130.85	90%	80%	21.02

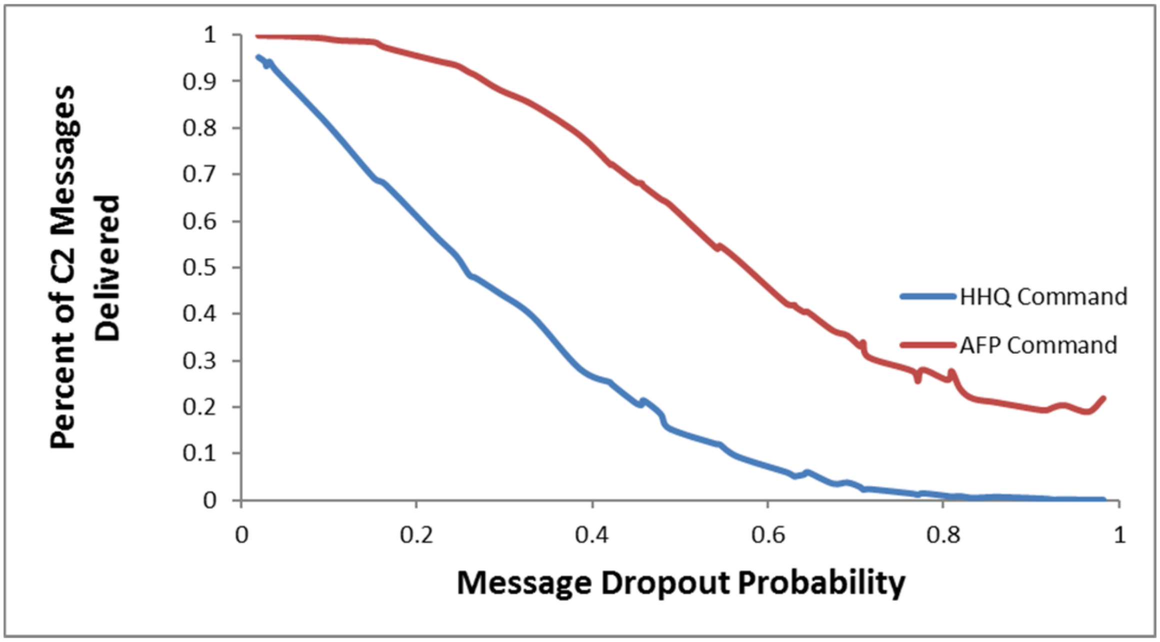

Figure 39. C2 Message Command Level Dropout Probability.

Figure 39 shows that the message dropout probability has a significant impact on C2 delivery success. The plot also shows that for networks in which the AFP is the command authority, the performance is significantly better in terms of C2 message delivery as the message dropout probability increases.

To compare statistically, a two-sample t-test is performed to determine the key metrics and compare the command authority to each other in a nominal environment where message dropout rate is constant. The simulation output data for Figure 39 test cases is located in Table A-4 of Appendix A, and the t-test analysis is available in 0 of Appendix C. Based on the P-values shown in Table 12 and Table 13, we can conclude the C2 message delivery time and time from request to engagement metrics are statistically significant between the command authority. As a result, it can be determined that OPORDs with the AFP commander as the decision authority will perform better than cases where HHQ is the command authority. This is as expected because there are fewer communication paths and interactions that need to occur and that the AFP commander will be more focused on the current mission compared to HHQ, which will be focused on multiple missions.

Table 12. Command Authority — C2 Message Delivery Success P-Value

Delivery Success	
Alternative Hypothesis	P-value
HHQ Authority < Local AFP Authority	4.95E-13

Table 13. Command Authority — Time from Request to Engagement P-Value

Time from Request to Engagement	
Alternative Hypothesis	P-value
HHQ Authority < Local AFP Authority	9.10E-23

The next statistical test is a paired t-test analysis where the message dropout rate applies a uniform distribution. The simulation output data and t-test analysis are shown in in Table C-5 of Appendix C. Based on the P-values shown in Table 14, we can conclude the C2 message delivery time and time from request to engagement metrics are statistically significant between decision authorities in a simulated contested spectrum environment. This result also supports the conclusion that performance is better when the AFP commander set as the decision authority (compared to HHQ as the command authority).

Table 14. Command Authority Dropout Rate Probability

Alternative Hypothesis	P-value
HHQ Authority < Local AFP Authority	2.79E-22

C. DESIGN OF EXPERIMENTS

A design of experiments (DOE) is performed based on the simulation parameters. The DOE analysis provides some insight into which of the simulation parameters affect the simulation output metrics. A full factorial DOE was designed choosing the simulation metrics described in Chapter V.A.3 as the responses and the simulation parameters described in Chapter V.A.2 as the factors. Based on the factors, the number of runs required for this full factorial is 288 runs. The DOE factors and values are shown in Table 15.

Table 15. Design of Experiment Factors

<table>
<tr><th rowspan="2">Factors</th><th colspan="4">Values</th></tr>
<tr><th colspan="2">Low</th><th colspan="2">High</th></tr>
<tr><td>NonC2 Message Processing time</td><td colspan="2">0.1</td><td colspan="2">2</td></tr>
<tr><td>C2 Message Processing time</td><td colspan="2">1.5</td><td colspan="2">5</td></tr>
<tr><td>NonC2 Message Receiving Processing Time</td><td colspan="2">0.1</td><td colspan="2">2</td></tr>
<tr><td>AFP C2 Message Receiving Processing Time</td><td colspan="2">60</td><td colspan="2">300</td></tr>
<tr><td>HHQ C2 Message Receiving Processing Time</td><td colspan="2">300</td><td colspan="2">1800</td></tr>
<tr><td>Dropout Rate</td><td>0</td><td colspan="2">0.35</td><td>0.6</td></tr>
<tr><td>Networks</td><td>Decentralized</td><td colspan="2">Distributed</td><td>Centralized</td></tr>
</table>

The following tables summarizing the DOE results show significant factors and the response variable sensitivity to each factor. The full set of DOE results are shown in Table A-5 of Appendix A. Each table describes log worth (-$\log_{10}$(p-value)) and p-values for each of the metric parameters.

1. C2 Message Delivery Success

Figure 40 shows the C2 message delivery success percentage response sensitivity analysis and P-values of all the factors.

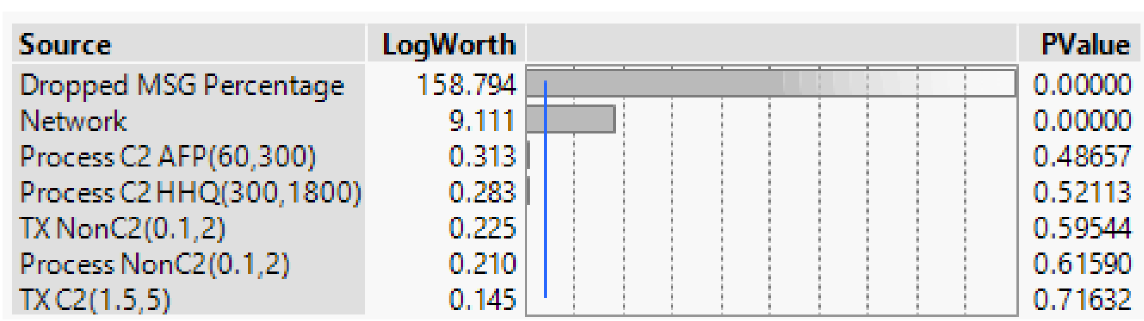

Figure 40. C2 Message Delivery Success Percentage.

Based on Figure 40, we can conclude that the dropout rate message percentage and the networks architecture factors are statistically significant for C2 message delivery success. Between those two factors, the log worth analysis shows that the C2 message delivery success percentage is notably more sensitive to the message dropout rate than the network architectures. Therefore, decreasing the number of dropped messages will have the biggest impact in increasing the C2 message delivery success percentage.

2. Non-C2 Message Delivery Success

Figure 41 shows the non-C2 message delivery success percentage response sensitivity analysis and P-values of all the factors.

Source	LogWorth	PValue
Dropped MSG Percentage	223.771	0.00000
Process C2 HHQ(300,1800)	0.512	0.30735
Process NonC2(0.1,2)	0.500	0.31619
TX C2(1.5,5)	0.499	0.31684
TX NonC2(0.1,2)	0.495	0.31983
Process C2 AFP(60,300)	0.455	0.35049
Network	0.438	0.36470

Figure 41. Non-C2 Message Delivery Success Percentage.

Based on Figure 41, we can conclude that the dropout rate message percentage is the only statistically significant factor for non-C2 message delivery success. The log worth analysis shows that the non-C2 message delivery success percentage is sensitive to the message dropout rate. Therefore, decreasing the number of dropped messages will have the biggest impact in increasing the non-C2 message delivery success percentage.

3. C2 Message Delivery Time

Figure 42 shows the C2 message delivery time response sensitivity analysis and P-values of all the factors.

Source	LogWorth	PValue
Process C2 AFP(60,300)	271.866	0.00000
TX C2(1.5,5)	22.649	0.00000
Dropped MSG Percentage	0.440	0.36306
Process C2 HHQ(300,1800)	0.413	0.38605
Process NonC2(0.1,2)	0.333	0.46434
Network	0.283	0.52126
TX NonC2(0.1,2)	0.093	0.80685

Figure 42. C2 Message Delivery Time.

Based on Figure 42, we can conclude that the time to process C2 messages in the AFP and the time to transmit C2 messages are statistically significant factors for C2 message delivery time. Between those two factors, the log worth analysis shows that the C2 message delivery time is notably more sensitive to the time to process C2 messages than the time to transmit C2 messages. Therefore, decreasing the time to process C2 messages in the AFP will have the biggest impact in decreasing the C2 message delivery time.

4. Non-C2 Message Delivery Time

Figure 43 shows the non-C2 message delivery time response sensitivity analysis and P-values of all the factors.

Source	LogWorth	PValue
TX NonC2(0.1,2)	1108.567	0.00000
Process NonC2(0.1,2)	1108.565	0.00000
Process C2 AFP(60,300)	0.397	0.40051
Network	0.384	0.41292
TX C2(1.5,5)	0.238	0.57783
Dropped MSG Percentage	0.236	0.58012
Process C2 HHQ(300,1800)	0.083	0.82669

Figure 43. Non-C2 Message Delivery Time.

Based on Figure 43, we can conclude that the time to process non-C2 messages in the AFP and the time to transmit non-C2 messages are statistically significant factors for non-C2 message delivery time. Between those two factors, the log worth analysis shows that the non-C2 message delivery time is equally sensitive to the time to process non-C2 messages and the time to transmit non-C2 messages. Therefore, decreasing the time to process non-C2 messages and the time to transmit non-C2 messages will have the biggest impact in decreasing the non-C2 message delivery time.

5. Time from Request to Engagement

Figure 44 shows the time from request to engagement response sensitivity analysis and P-values of all the factors.

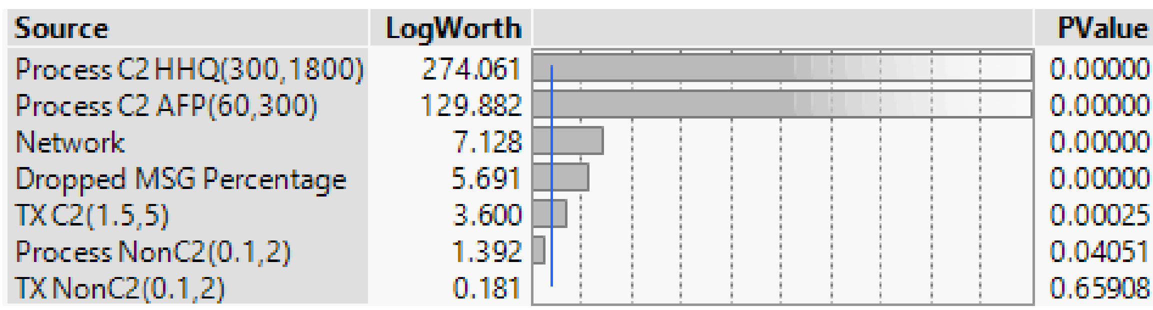

Figure 44. Time from Request to Engagement.

Based on Figure 44, we can conclude multiple factors are statistically significant for time from request to engagement. Between these factors, the log worth analysis shows that the time from request to engagement is most sensitive to the C2 processing time at HHQ and the AFP. Therefore, decreasing the time it takes commanders and HHQ to process C2 messages will have the biggest impact in decreasing the time from request to engagement.

D. MODEL VERIFICATION

Model performance is verified by comparing the results of the test cases to expected results based on back of the envelope (BOE) calculations. The back of the envelope equations for the three networks are derived as followed:

$$MSP_{Distributed} = \frac{1}{5}(1-MDR)^2 + \frac{4}{5}(1-MDR)^2 * (1-MDR^{(Nodes-1)})^2 \qquad (1)$$

$$MSP_{Decentralized} = \frac{1}{5}(1-MDR)^2 + \frac{4}{5}(1-MDR)^2 * (1-MDR^{(Nodes-3)})^2 \qquad (2)$$

$$MSP_{Centralized} = \frac{1}{5}(1-MDR)^2 + \frac{4}{5}(1-MDR)^4 \qquad (3)$$

$$MSP_{(Distributed,noHHQ)} = \frac{1}{5} + \frac{4}{5}(1-MDR^{(Nodes-1)})^2 \qquad (4)$$

where MSP is the message success percentage, MDR is the message dropout rate, and nodes are the number of nodes in the AFP. For the analysis, the number of nodes is five. The back of the envelope calculations are compared to the model results in Table 16.

Table 16. Model Validation

MSP_{BOE} | MSP_{Model}								
MDR	Distributed		Decentralized		Centralized		Distributed, No HHQ	
0.1	81%	80%	80%	79%	69%	69%	98%	99%
0.2	63%	61%	60%	55%	45%	45%	94%	95%
0.5	22%	15%	16%	13%	10%	10%	65%	61%

The table shows the model results are consistent with the BOE calculations. The reason the model MSP is lower at a high MDR is because the BOE does not account for instances where messages are lost during transmission to the C2 forwarder and the other platforms simultaneously. This event would be rare at a low MDR but it would be more common at a high MDR, which would explain the 3%–7% difference between the model and BOE.

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VI. CONCLUSION

The geographical dispersion of naval forces operating under the distributed lethality concept introduces operational challenges to traditional C2 across an AFP due to the long distances required for communications, the anticipated disruption of satellite communications, and the relatively close proximity of opposing forces. Tactical C2 systems must be flexible to support changing communication architectures. Operational C2 must be flexible to work within the boundaries of the available communication architectures. This research project employs MBSE methods to better understand and improve the capability of naval forces operating under the distributed lethality concept.

A. SUMMARY OF FINDINGS

<u>C2 Network Architecture</u>: The use of MBSE and statistical analysis of computer simulation of C2 network architectures confirms the hypothesis that a distributed mesh architecture is the most robust for distributed lethality C2 networks.

<u>C2 Process Model</u>: Model based systems engineering identifies possible efficiencies to the traditional C2 process model that can improve the effectiveness of C2 when operating within the constraints of distributed lethality. Statistical analysis of computer simulation of C2 networks and process models confirms the benefit.

<u>Advanced Tactical Data Links</u>: Review of available and near future advanced tactical data links finds no 100% solution in a single system. Additionally, the distributed lethality AFP needs multiple tactical data link options to build a distributed mesh network architecture. The need for interoperability among all AFP platforms requires common data links. USN, USNS, joint, and coalition forces will potentially participate in distributed lethality operations as part of an AFP.

Platforms without common datalinks must be modified to add this capability if they are to participate in the AFP C2 network. Advanced tactical data links must be interoperable on Link 16 and Link 22 to meet the joint and coalition interoperability requirement. AFP C2 systems should include provisions for the joint range extension protocol (JREAP) for use when IP networks or satellite communications are available.

Distributed lethality AFP platforms will benefit from technology updates that improve automated network discovery by:

- adding a link monitoring and management tool to identify and correct disruptions in tactical data link networks
- utilizing an external time reference to aid tactical data link network synchronization
- employing smart command and control processor data routing to optimize routing and eliminate redundant messages

Distributed lethality AFP platforms will also improve C2 network operations by adding directional antenna systems to the tactical data link systems. Directional antennas will shift from omnidirectional radio frequency radiation patterns to a controlled narrow beam path directed to other participants of the AFP C2 network. Benefits of directional antennas include lower probability of detection of the radiated signal, adding nulling patterns to reduce spectrum interference from hostile sources, and lower power output requirements for transmitters because a directional antenna focuses the RF signal using fewer radiating elements than an omnidirectional antenna.

C2 Concepts: Functional analysis supporting distributed lethality C2 use systems architecture to evaluate different C2 concepts for an AFP. The architecture is driven by Naval Postgraduate School wargame scenarios based upon real world environments. The system of system architecture model provides a structure for simulating C2 decisions and evaluating if changes will provide a method for improvements.

Model based systems engineering captures C2 sub-functions and architecture, separates them from the OPORD, and allocates distributed lethality requirements into C2 as sub-functions. This approach allows OPORD evaluation as a distinct portion of the physical architecture, and further enables evaluation of the C2 structure by simulation of the kill chain. Computer model simulations focus on internal communication and external communication components of the distributed lethality C2 architecture, as well as the presence or absence of an OPORD, and the impacts to the overall mission execution as specific measures of effectiveness are modified.

B. RECOMMENDATIONS

Independent Review of Results: Obtain an independent review of the models and architectures to confirm model validity and analysis results. Distributed lethality models are evolving as the concept matures. An independent review may validate the C2 network models or yield recommendations to modify the models and architectures for better alignment with distributed lethality concepts.

Model Additional Wargame Scenarios: Examine the effectiveness of the recommended OPORD and networking changes across other scenarios and AFP compositions from the cited wargame studies. The analysis may identify scenarios where the recommend changes for distributed lethality OPORD and C2 networking is not effective or, may actually reduce operational effectiveness. Understanding the limitations of distributed lethality may be as important to the Navy as understanding its benefits.

Higher Fidelity Modeling and Simulation: Time constraints and public releasability of this research did not permit hi-fidelity modeling of tactical datalinks. Further development of scenarios utilizing autonomous aerial, surface, and subsurface vehicles operating as communications relays and sensors within the AFP could provide additional benefits. Additional modeling and simulation incorporating higher fidelity of communications systems and sensors will advance the distributed lethality concept and improve operational effectiveness.

C. ADDITIONAL RESEARCH RECOMMENDATIONS

Additional research, beyond the scope of this study, is recommended for directional smart antenna controllers to reduce the probably of detection due to the omnidirectional nature of legacy C2 waveforms (Northrop Grumman 2016). The C2 waveform should only transmit to other units within the AFP with a directional BLOS/LOS waveform to reduce the probably of detection.

As the largest simulated impact to the measure of effectiveness was shown to be the functionality of the OPORD at the AFP commander level, it is proposed that further research is warranted in the construction of an updated OPORD specifically for distributed lethality C2 architectures.

This paper establishes a basis for C2 MBSE modeling and simulation. Further research and refinement of the physical and functional architecture remains to be developed.

APPENDIX A. SIMULATION RESULTS

Table A-1 Test Case 1 Data

	Distributed Network				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	81.7%	90.0%	128.0	0.200	1249.6
2	80.5%	89.8%	131.6	0.200	1269.7
3	80.4%	89.8%	131.4	0.200	1258.0
4	80.7%	90.1%	131.5	0.200	1257.9
5	79.3%	89.9%	130.9	0.200	1270.2
6	78.0%	90.0%	131.2	0.200	1274.5
7	81.4%	90.0%	130.2	0.200	1256.6
8	80.8%	90.1%	130.8	0.200	1259.2
9	80.9%	89.9%	131.7	0.200	1259.6
10	80.3%	90.0%	131.1	0.200	1259.3
	Decentralized Network				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	79.9%	89.8%	128.7	0.200	1279.5
2	78.9%	90.0%	130.3	0.200	1284.3
3	79.7%	90.0%	131.5	0.200	1272.2
4	77.9%	90.1%	130.0	0.200	1262.4
5	78.9%	90.1%	128.9	0.200	1253.3
6	77.7%	90.1%	130.5	0.200	1277.9
7	79.1%	89.9%	130.9	0.200	1289.4
8	79.2%	90.0%	129.9	0.200	1285.3
9	79.0%	90.2%	129.0	0.200	1272.6
10	78.5%	90.2%	130.2	0.200	1275.2
	Centralized				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	66.2%	89.9%	129.3	0.200	1280.8
2	68.6%	89.9%	129.6	0.200	1283.4
3	68.8%	90.1%	130.4	0.200	1284.2
4	66.7%	90.2%	132.1	0.200	1291.0
5	68.7%	90.3%	130.1	0.200	1313.5
6	68.7%	90.2%	129.0	0.200	1287.3
7	67.3%	90.0%	131.1	0.200	1287.3
8	69.9%	90.3%	130.4	0.200	1284.2
9	66.9%	89.9%	129.0	0.200	1282.6
10	70.0%	90.2%	130.7	0.200	1298.1

Table A-2 Test Case 2 Data

	DDG 1				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	78.9%	89.9%	130.3	0.200	1258.1
2	81.3%	90.1%	131.0	0.200	1268.3
3	80.2%	90.1%	130.5	0.200	1266.5
4	80.7%	90.0%	130.5	0.200	1275.9
5	80.7%	90.1%	128.7	0.200	1248.6
6	81.9%	90.1%	128.2	0.200	1258.9
7	79.5%	89.9%	129.1	0.200	1246.0
8	81.5%	90.0%	130.4	0.200	1258.1
9	80.3%	89.9%	130.7	0.200	1261.9
10	82.6%	90.0%	131.5	0.200	1256.5
	DDG2				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	82.5%	90.0%	127.6	0.200	1263.8
2	77.7%	89.8%	131.8	0.200	1269.8
3	81.3%	90.1%	127.8	0.200	1251.7
4	80.9%	90.0%	131.2	0.200	1265.5
5	81.0%	89.9%	130.1	0.200	1253.2
6	81.1%	89.9%	130.3	0.200	1266.9
7	79.2%	89.8%	132.4	0.200	1267.9
8	79.4%	89.9%	131.0	0.200	1266.9
9	81.2%	90.1%	132.6	0.200	1269.2
10	80.4%	90.0%	130.7	0.200	1245.5
	LCS1				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	80.6%	90.0%	131.5	0.200	1276.4
2	80.3%	90.1%	130.5	0.200	1260.7
3	80.8%	90.1%	129.6	0.200	1260.0
4	82.0%	90.0%	129.9	0.200	1265.6
5	79.3%	89.8%	128.7	0.200	1252.6
6	79.7%	90.0%	129.8	0.200	1254.7
7	79.9%	90.1%	130.8	0.200	1258.6
8	78.9%	89.9%	129.6	0.200	1269.2
9	81.3%	90.0%	130.1	0.200	1261.5
10	79.6%	90.0%	129.5	0.200	1255.6
	LCS2				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	81.7%	90.0%	128.0	0.200	1249.6
2	80.5%	89.8%	131.6	0.200	1269.7
3	80.4%	89.8%	131.4	0.200	1258.0
4	80.7%	90.1%	131.5	0.200	1257.9
5	79.3%	89.9%	130.9	0.200	1270.2
6	78.0%	90.0%	131.2	0.200	1274.5
7	81.4%	90.0%	130.2	0.200	1256.6
8	80.8%	90.1%	130.8	0.200	1259.2
9	80.9%	89.9%	131.7	0.200	1259.6
10	80.3%	90.0%	131.1	0.200	1259.3
	LCS3				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	79.8%	90.1%	130.0	0.200	1252.1
2	79.6%	90.0%	132.0	0.200	1264.9
3	81.2%	90.0%	128.8	0.200	1262.5
4	79.9%	90.0%	129.2	0.200	1259.0
5	79.9%	90.0%	130.2	0.200	1242.0
6	80.3%	90.0%	129.8	0.200	1263.0
7	80.2%	89.9%	130.5	0.200	1273.7
8	81.0%	89.9%	130.3	0.200	1257.3
9	80.0%	90.0%	130.7	0.200	1255.4
10	80.1%	89.9%	131.0	0.200	1258.3

Table A-3 Test Case 3 Data

Message Dropout Rate	Distributed C2 Success	Centralized C2 Success	Decentralized C2 Success
2.0%	95.3%	93.0%	96.7%
2.7%	94.3%	90.9%	94.6%
2.9%	93.4%	90.5%	94.7%
3.2%	94.4%	89.4%	93.4%
3.9%	92.6%	86.9%	92.2%
8.8%	83.1%	70.8%	80.1%
11.2%	77.9%	64.3%	76.8%
15.2%	69.2%	55.3%	67.0%
16.4%	68.0%	53.5%	64.2%
22.2%	56.7%	40.6%	50.2%
24.5%	52.5%	37.0%	48.6%
26.0%	48.4%	35.6%	44.4%
26.8%	47.7%	35.3%	44.9%
29.4%	44.5%	30.5%	38.1%
33.2%	39.5%	24.0%	33.9%
38.5%	28.2%	18.8%	26.0%
42.1%	25.3%	15.7%	21.1%
42.1%	25.0%	14.6%	19.6%
44.9%	20.9%	13.5%	17.8%
45.6%	20.4%	12.5%	16.7%
45.8%	21.4%	13.5%	15.9%
47.8%	18.5%	11.2%	15.8%
48.7%	15.4%	11.3%	14.4%
54.2%	12.0%	6.7%	9.0%
54.4%	12.0%	7.9%	8.9%
56.5%	9.3%	6.8%	7.8%
62.1%	5.9%	4.8%	4.9%
63.0%	5.0%	3.6%	5.0%
63.1%	5.1%	4.0%	5.1%
64.1%	5.5%	3.6%	3.7%
64.5%	6.0%	3.9%	4.0%
67.3%	3.5%	2.6%	3.9%
69.0%	3.7%	2.8%	2.9%
70.5%	2.8%	2.4%	1.9%
70.8%	2.2%	2.4%	2.4%
71.4%	2.4%	1.5%	2.9%
76.5%	1.3%	1.1%	1.2%
77.0%	1.1%	1.2%	1.3%
77.6%	1.4%	1.2%	1.0%
80.4%	0.8%	1.0%	0.5%
80.9%	0.7%	1.1%	1.0%
81.9%	0.8%	1.2%	0.8%
83.3%	0.4%	0.5%	0.6%
85.9%	0.6%	0.5%	0.2%
91.2%	0.3%	0.1%	0.1%
91.9%	0.2%	0.1%	0.2%
92.5%	0.1%	0.2%	0.2%
93.8%	0.1%	0.2%	0.1%
96.4%	0.0%	0.0%	0.1%
98.1%	0.0%	0.0%	0.1%

Table A-4 Test Case 4 Data

	HHQ Decision Authority				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	81.7%	90.0%	128.0	0.200	1249.6
2	80.5%	89.8%	131.6	0.200	1269.7
3	80.4%	89.8%	131.4	0.200	1258.0
4	80.7%	90.1%	131.5	0.200	1257.9
5	79.3%	89.9%	130.9	0.200	1270.2
6	78.0%	90.0%	131.2	0.200	1274.5
7	81.4%	90.0%	130.2	0.200	1256.6
8	80.8%	90.1%	130.8	0.200	1259.2
9	80.9%	89.9%	131.7	0.200	1259.6
10	80.3%	90.0%	131.1	0.200	1259.3
	Local AFP Decision Authority				
Run	C2 Success Perc	Non C2 Success Perc	C2 Mean Deliv	Non C2 Mean Deliv	RQT2ENG
1	99.5%	90.1%	132.6	0.200	263.1
2	99.3%	89.9%	128.5	0.200	259.2
3	99.0%	90.0%	132.6	0.200	262.1
4	99.4%	89.9%	129.1	0.200	258.4
5	99.3%	89.9%	129.2	0.200	259.6
6	99.5%	90.0%	130.3	0.200	259.2
7	99.3%	90.1%	131.0	0.200	261.1
8	99.3%	90.0%	131.0	0.200	259.8
9	99.2%	90.0%	129.9	0.200	259.0
10	99.4%	90.0%	130.3	0.200	261.0

Message Dropout Rate	HHQ Decision Authority	Local AFP Decision Authority
2.0%	95.3%	99.9%
2.7%	94.3%	99.9%
2.9%	93.4%	99.9%
3.2%	94.4%	99.8%
3.9%	92.6%	99.9%
8.8%	83.1%	99.4%
11.2%	77.9%	98.9%
15.2%	69.2%	98.5%
16.4%	68.0%	97.4%
22.2%	56.7%	94.5%
24.5%	52.5%	93.5%
26.0%	48.4%	92.0%
26.8%	47.7%	91.3%
29.4%	44.5%	88.2%
33.2%	39.5%	85.1%
38.5%	28.2%	78.5%
42.1%	25.3%	72.1%
42.1%	25.0%	72.4%
44.9%	20.9%	68.4%
45.6%	20.4%	68.2%
45.8%	21.4%	67.5%
47.8%	18.5%	64.7%
48.7%	15.4%	63.7%
54.2%	12.0%	54.1%
54.4%	12.0%	54.7%
56.5%	9.3%	51.8%
62.1%	5.9%	42.2%
63.0%	5.0%	42.0%
63.1%	5.1%	41.5%
64.1%	5.5%	40.4%
64.5%	6.0%	40.5%
67.3%	3.5%	36.5%
69.0%	3.7%	35.4%
70.5%	2.8%	33.0%
70.8%	2.2%	33.9%
71.4%	2.4%	30.7%
76.5%	1.3%	27.7%
77.0%	1.1%	25.5%
77.6%	1.4%	28.0%
80.4%	0.8%	25.8%
80.9%	0.7%	27.7%
81.9%	0.8%	23.9%
83.3%	0.4%	21.8%
85.9%	0.6%	21.0%
91.2%	0.3%	19.3%
91.9%	0.2%	19.4%
92.5%	0.1%	19.9%
93.8%	0.1%	20.3%
96.4%	0.0%	19.0%
98.1%	0.0%	21.9%

Table A-5 Design of Experiment Data

Run	TX nonC2	TX C2	Processnon C2	Process C2 AFP	Process C2 HHQ	Network	Dropped MSG	C2 Success percentange	NonC2 success percentage	C2 delivery time	Non-C2 delivery time	Time from RQT to ENG
1	0.1	1.5	0.1	60	300	Distributed	0.1	79.2%	90.1%	112.8	0.200	1028.3
2	0.1	1.5	0.1	60	300	Distributed	0.35	35.6%	65.1%	112.5	0.200	1067.0
3	0.1	1.5	0.1	60	300	Distributed	0.6	7.4%	39.9%	114.7	0.200	1012.1
4	0.1	1.5	0.1	60	300	Centralized	0.1	69.3%	89.9%	114.8	0.200	1054.8
5	0.1	1.5	0.1	60	300	Centralized	0.35	22.4%	64.9%	107.8	0.200	1075.7
6	0.1	1.5	0.1	60	300	Centralized	0.6	4.9%	40.1%	116.3	0.200	1149.8
7	0.1	1.5	0.1	60	300	Decentralized	0.1	79.5%	89.9%	116.0	0.200	1056.4
8	0.1	1.5	0.1	60	300	Decentralized	0.35	31.5%	65.2%	113.3	0.200	1046.4
9	0.1	1.5	0.1	60	300	Decentralized	0.6	7.4%	40.2%	116.7	0.200	1072.0
10	0.1	1.5	0.1	60	1800	Distributed	0.1	81.3%	90.1%	114.1	0.200	1529.7
11	0.1	1.5	0.1	60	1800	Distributed	0.35	36.0%	64.7%	118.0	0.200	1532.5
12	0.1	1.5	0.1	60	1800	Distributed	0.6	7.4%	40.0%	113.8	0.200	1522.7
13	0.1	1.5	0.1	60	1800	Centralized	0.1	69.9%	89.7%	114.2	0.200	1560.4
14	0.1	1.5	0.1	60	1800	Centralized	0.35	23.3%	65.0%	115.1	0.200	1553.1
15	0.1	1.5	0.1	60	1800	Centralized	0.6	4.6%	40.3%	113.8	0.200	1601.7
16	0.1	1.5	0.1	60	1800	Decentralized	0.1	78.3%	90.0%	114.1	0.200	1540.4
17	0.1	1.5	0.1	60	1800	Decentralized	0.35	28.7%	64.9%	118.6	0.200	1542.1
18	0.1	1.5	0.1	60	1800	Decentralized	0.6	5.7%	40.1%	115.1	0.200	1534.1
19	0.1	1.5	0.1	300	300	Distributed	0.1	79.7%	90.0%	179.5	0.200	1169.8
20	0.1	1.5	0.1	300	300	Distributed	0.35	34.3%	65.0%	176.0	0.200	1186.3
21	0.1	1.5	0.1	300	300	Distributed	0.6	8.2%	40.1%	174.1	0.200	1251.0
22	0.1	1.5	0.1	300	300	Centralized	0.1	68.9%	90.1%	177.4	0.200	1211.0
23	0.1	1.5	0.1	300	300	Centralized	0.35	22.3%	64.9%	174.7	0.200	1224.6
24	0.1	1.5	0.1	300	300	Centralized	0.6	5.2%	40.1%	189.2	0.200	1247.1
25	0.1	1.5	0.1	300	300	Decentralized	0.1	79.3%	90.0%	176.4	0.200	1166.5
26	0.1	1.5	0.1	300	300	Decentralized	0.35	31.3%	64.9%	178.0	0.200	1200.6
27	0.1	1.5	0.1	300	300	Decentralized	0.6	6.3%	39.8%	173.8	0.200	1158.9
28	0.1	1.5	0.1	300	1800	Distributed	0.1	80.9%	90.1%	179.0	0.200	1649.2
29	0.1	1.5	0.1	300	1800	Distributed	0.35	35.8%	65.2%	178.0	0.200	1701.2
30	0.1	1.5	0.1	300	1800	Distributed	0.6	6.2%	40.0%	179.1	0.200	1664.6
31	0.1	1.5	0.1	300	1800	Centralized	0.1	70.9%	89.9%	177.4	0.200	1691.7
32	0.1	1.5	0.1	300	1800	Centralized	0.35	25.1%	65.1%	177.2	0.200	1689.2
33	0.1	1.5	0.1	300	1800	Centralized	0.6	6.0%	40.0%	181.1	0.200	1741.7
34	0.1	1.5	0.1	300	1800	Decentralized	0.1	79.0%	89.9%	176.8	0.200	1684.5
35	0.1	1.5	0.1	300	1800	Decentralized	0.35	31.4%	65.1%	178.4	0.200	1704.4
36	0.1	1.5	0.1	300	1800	Decentralized	0.6	6.6%	40.1%	180.1	0.200	1665.6
37	0.1	1.5	2	60	300	Distributed	0.1	81.3%	90.1%	112.6	2.100	1023.2
38	0.1	1.5	2	60	300	Distributed	0.35	34.3%	65.0%	117.6	2.100	1061.0
39	0.1	1.5	2	60	300	Distributed	0.6	6.2%	40.0%	109.2	2.100	1118.5
40	0.1	1.5	2	60	300	Centralized	0.1	69.4%	90.1%	113.7	2.100	1064.2
41	0.1	1.5	2	60	300	Centralized	0.35	21.0%	65.3%	110.2	2.100	1064.2
42	0.1	1.5	2	60	300	Centralized	0.6	6.1%	39.9%	115.4	2.100	1081.8
43	0.1	1.5	2	60	300	Decentralized	0.1	79.0%	90.2%	117.5	2.100	1040.8
44	0.1	1.5	2	60	300	Decentralized	0.35	28.7%	65.1%	117.4	2.100	1057.2
45	0.1	1.5	2	60	300	Decentralized	0.6	7.3%	39.9%	116.1	2.100	1053.5
46	0.1	1.5	2	60	1800	Distributed	0.1	79.2%	90.0%	116.1	2.100	1509.9
47	0.1	1.5	2	60	1800	Distributed	0.35	34.1%	65.2%	113.4	2.100	1525.0
48	0.1	1.5	2	60	1800	Distributed	0.6	7.3%	40.1%	112.1	2.100	1612.8
49	0.1	1.5	2	60	1800	Centralized	0.1	68.2%	90.0%	116.4	2.100	1561.9
50	0.1	1.5	2	60	1800	Centralized	0.35	23.2%	64.8%	110.7	2.100	1542.8
51	0.1	1.5	2	60	1800	Centralized	0.6	4.6%	40.3%	118.4	2.100	1467.4
52	0.1	1.5	2	60	1800	Decentralized	0.1	79.7%	90.0%	113.8	2.100	1544.7
53	0.1	1.5	2	60	1800	Decentralized	0.35	31.6%	65.0%	113.3	2.100	1585.3
54	0.1	1.5	2	60	1800	Decentralized	0.6	6.3%	40.1%	112.2	2.100	1485.4
55	0.1	1.5	2	300	300	Distributed	0.1	81.4%	90.0%	179.8	2.100	1159.1
56	0.1	1.5	2	300	300	Distributed	0.35	34.7%	64.8%	178.2	2.100	1190.2
57	0.1	1.5	2	300	300	Distributed	0.6	7.3%	40.2%	177.6	2.100	1204.0
58	0.1	1.5	2	300	300	Centralized	0.1	67.6%	90.0%	179.1	2.100	1211.1
59	0.1	1.5	2	300	300	Centralized	0.35	23.9%	65.0%	178.6	2.100	1188.9
60	0.1	1.5	2	300	300	Centralized	0.6	6.0%	40.3%	178.7	2.100	1300.5
61	0.1	1.5	2	300	300	Decentralized	0.1	77.5%	89.9%	177.8	2.100	1194.6
62	0.1	1.5	2	300	300	Decentralized	0.35	29.9%	64.9%	178.2	2.100	1165.4
63	0.1	1.5	2	300	300	Decentralized	0.6	7.3%	39.8%	186.6	2.100	1210.1
64	0.1	1.5	2	300	1800	Distributed	0.1	80.1%	90.1%	176.8	2.100	1657.2
65	0.1	1.5	2	300	1800	Distributed	0.35	34.7%	65.2%	177.9	2.100	1696.9
66	0.1	1.5	2	300	1800	Distributed	0.6	6.3%	39.8%	174.5	2.100	1710.0
67	0.1	1.5	2	300	1800	Centralized	0.1	69.2%	89.8%	177.3	2.100	1704.0
68	0.1	1.5	2	300	1800	Centralized	0.35	24.5%	65.1%	180.2	2.100	1712.5
69	0.1	1.5	2	300	1800	Centralized	0.6	6.0%	40.1%	170.4	2.100	1673.7
70	0.1	1.5	2	300	1800	Decentralized	0.1	77.4%	90.0%	177.4	2.100	1687.2
71	0.1	1.5	2	300	1800	Decentralized	0.35	28.3%	65.0%	177.6	2.100	1693.4
72	0.1	1.5	2	300	1800	Decentralized	0.6	4.8%	39.6%	183.6	2.100	1661.9
73	0.1	5	0.1	60	300	Distributed	0.1	81.1%	89.9%	117.5	0.200	1043.0
74	0.1	5	0.1	60	300	Distributed	0.35	34.0%	64.9%	118.6	0.200	1046.1
75	0.1	5	0.1	60	300	Distributed	0.6	7.4%	39.9%	111.6	0.200	1039.4
76	0.1	5	0.1	60	300	Centralized	0.1	67.6%	90.1%	118.7	0.200	1076.4
77	0.1	5	0.1	60	300	Centralized	0.35	20.8%	65.2%	121.6	0.200	1050.6
78	0.1	5	0.1	60	300	Centralized	0.6	4.8%	39.9%	121.6	0.200	1139.3
79	0.1	5	0.1	60	300	Decentralized	0.1	77.9%	90.1%	120.9	0.200	1039.8
80	0.1	5	0.1	60	300	Decentralized	0.35	28.9%	65.0%	121.1	0.200	1063.6
81	0.1	5	0.1	60	300	Decentralized	0.6	6.1%	39.8%	125.6	0.200	1054.7
82	0.1	5	0.1	60	1800	Distributed	0.1	81.4%	90.1%	118.5	0.200	1549.8
83	0.1	5	0.1	60	1800	Distributed	0.35	34.3%	65.2%	118.1	0.200	1538.8
84	0.1	5	0.1	60	1800	Distributed	0.6	5.7%	39.9%	113.9	0.200	1575.6
85	0.1	5	0.1	60	1800	Centralized	0.1	68.6%	90.0%	117.5	0.200	1585.3
86	0.1	5	0.1	60	1800	Centralized	0.35	22.3%	64.9%	122.5	0.200	1557.2
87	0.1	5	0.1	60	1800	Centralized	0.6	5.3%	39.7%	122.8	0.200	1600.2
88	0.1	5	0.1	60	1800	Decentralized	0.1	78.4%	90.0%	117.5	0.200	1552.5
89	0.1	5	0.1	60	1800	Decentralized	0.35	31.0%	65.2%	119.9	0.200	1567.2
90	0.1	5	0.1	60	1800	Decentralized	0.6	5.7%	40.1%	113.5	0.200	1615.6
91	0.1	5	0.1	300	300	Distributed	0.1	79.8%	90.0%	183.0	0.200	1185.2
92	0.1	5	0.1	300	300	Distributed	0.35	35.0%	64.9%	189.1	0.200	1220.3
93	0.1	5	0.1	300	300	Distributed	0.6	8.5%	40.1%	181.4	0.200	1234.3
94	0.1	5	0.1	300	300	Centralized	0.1	66.8%	90.0%	184.2	0.200	1233.0
95	0.1	5	0.1	300	300	Centralized	0.35	23.2%	64.9%	187.1	0.200	1223.8
96	0.1	5	0.1	300	300	Centralized	0.6	5.5%	40.6%	178.6	0.200	1255.3

97	0.1	5	0.1	300	300	Decentralized	0.1	79.2%	90.0%	182.0	0.200	1199.0
98	0.1	5	0.1	300	300	Decentralized	0.35	30.8%	65.0%	180.1	0.200	1173.4
99	0.1	5	0.1	300	300	Decentralized	0.6	7.0%	40.0%	181.1	0.200	1157.9
100	0.1	5	0.1	300	1800	Distributed	0.1	80.7%	90.1%	184.1	0.200	1666.3
101	0.1	5	0.1	300	1800	Distributed	0.35	35.5%	65.1%	184.6	0.200	1698.4
102	0.1	5	0.1	300	1800	Distributed	0.6	7.8%	40.0%	185.9	0.200	1781.0
103	0.1	5	0.1	300	1800	Centralized	0.1	68.9%	89.9%	180.5	0.200	1719.9
104	0.1	5	0.1	300	1800	Centralized	0.35	22.9%	64.8%	184.2	0.200	1679.0
105	0.1	5	0.1	300	1800	Centralized	0.6	5.6%	39.9%	186.9	0.200	1669.7
106	0.1	5	0.1	300	1800	Decentralized	0.1	79.1%	90.0%	183.0	0.200	1695.9
107	0.1	5	0.1	300	1800	Decentralized	0.35	31.4%	64.8%	183.3	0.200	1733.3
108	0.1	5	0.1	300	1800	Decentralized	0.6	5.8%	40.1%	181.8	0.200	1709.6
109	0.1	5	2	60	300	Distributed	0.1	79.0%	90.0%	118.8	2.100	1014.7
110	0.1	5	2	60	300	Distributed	0.35	37.0%	65.1%	118.8	2.100	1041.7
111	0.1	5	2	60	300	Distributed	0.6	7.6%	40.0%	128.1	2.100	1117.8
112	0.1	5	2	60	300	Centralized	0.1	66.5%	90.3%	119.2	2.100	1058.7
113	0.1	5	2	60	300	Centralized	0.35	23.3%	65.1%	120.3	2.100	1093.5
114	0.1	5	2	60	300	Centralized	0.6	5.8%	39.9%	125.4	2.100	1033.1
115	0.1	5	2	60	300	Decentralized	0.1	79.3%	90.0%	118.9	2.100	1070.0
116	0.1	5	2	60	300	Decentralized	0.35	28.4%	65.1%	120.0	2.100	1072.1
117	0.1	5	2	60	300	Decentralized	0.6	6.5%	40.2%	114.7	2.100	1051.8
118	0.1	5	2	60	1800	Distributed	0.1	82.4%	90.0%	118.8	2.100	1541.4
119	0.1	5	2	60	1800	Distributed	0.35	33.3%	65.1%	119.8	2.100	1571.7
120	0.1	5	2	60	1800	Distributed	0.6	6.9%	40.0%	110.9	2.100	1524.0
121	0.1	5	2	60	1800	Centralized	0.1	69.4%	90.0%	121.3	2.100	1583.1
122	0.1	5	2	60	1800	Centralized	0.35	21.1%	65.0%	120.5	2.100	1560.4
123	0.1	5	2	60	1800	Centralized	0.6	5.1%	39.8%	110.8	2.100	1555.1
124	0.1	5	2	60	1800	Decentralized	0.1	77.5%	90.0%	119.6	2.100	1553.7
125	0.1	5	2	60	1800	Decentralized	0.35	29.3%	65.0%	120.9	2.100	1546.2
126	0.1	5	2	60	1800	Decentralized	0.6	6.4%	40.1%	118.8	2.100	1575.9
127	0.1	5	2	300	300	Distributed	0.1	80.1%	90.1%	184.1	2.100	1175.2
128	0.1	5	2	300	300	Distributed	0.35	33.7%	65.2%	183.7	2.100	1174.6
129	0.1	5	2	300	300	Distributed	0.6	7.7%	40.0%	184.3	2.100	1180.1
130	0.1	5	2	300	300	Centralized	0.1	67.9%	90.0%	180.0	2.100	1206.6
131	0.1	5	2	300	300	Centralized	0.35	24.0%	64.9%	183.0	2.100	1209.0
132	0.1	5	2	300	300	Centralized	0.6	5.4%	40.0%	190.0	2.100	1191.1
133	0.1	5	2	300	300	Decentralized	0.1	78.6%	90.0%	184.6	2.100	1200.9
134	0.1	5	2	300	300	Decentralized	0.35	29.6%	64.9%	183.6	2.100	1198.2
135	0.1	5	2	300	300	Decentralized	0.6	6.9%	39.9%	178.0	2.100	1148.7
136	0.1	5	2	300	1800	Distributed	0.1	80.4%	90.1%	181.0	2.100	1648.8
137	0.1	5	2	300	1800	Distributed	0.35	36.1%	65.1%	184.7	2.100	1692.3
138	0.1	5	2	300	1800	Distributed	0.6	7.6%	40.3%	180.9	2.100	1695.7
139	0.1	5	2	300	1800	Centralized	0.1	66.8%	89.9%	182.4	2.100	1723.8
140	0.1	5	2	300	1800	Centralized	0.35	22.5%	64.7%	184.4	2.100	1716.8
141	0.1	5	2	300	1800	Centralized	0.6	6.2%	39.8%	183.1	2.100	1789.4
142	0.1	5	2	300	1800	Decentralized	0.1	78.9%	89.9%	183.2	2.100	1695.9
143	0.1	5	2	300	1800	Decentralized	0.35	31.5%	64.9%	181.5	2.100	1701.0
144	0.1	5	2	300	1800	Decentralized	0.6	6.4%	40.1%	178.4	2.100	1706.3
145	2	1.5	0.1	60	300	Distributed	0.1	80.7%	90.0%	113.5	2.100	1040.5
146	2	1.5	0.1	60	300	Distributed	0.35	36.3%	65.0%	114.4	2.100	1053.0
147	2	1.5	0.1	60	300	Distributed	0.6	5.9%	40.1%	110.7	2.100	1026.4
148	2	1.5	0.1	60	300	Centralized	0.1	68.0%	89.8%	112.0	2.100	1043.0
149	2	1.5	0.1	60	300	Centralized	0.35	22.1%	65.1%	117.1	2.100	1077.0
150	2	1.5	0.1	60	300	Centralized	0.6	6.1%	40.2%	126.0	2.100	1066.6
151	2	1.5	0.1	60	300	Decentralized	0.1	78.7%	90.1%	115.7	2.100	1038.2
152	2	1.5	0.1	60	300	Decentralized	0.35	29.6%	65.2%	116.1	2.100	1063.9
153	2	1.5	0.1	60	300	Decentralized	0.6	6.4%	40.0%	115.7	2.100	1000.1
154	2	1.5	0.1	60	1800	Distributed	0.1	79.7%	89.9%	115.1	2.100	1530.3
155	2	1.5	0.1	60	1800	Distributed	0.35	37.2%	64.8%	114.3	2.100	1541.1
156	2	1.5	0.1	60	1800	Distributed	0.6	8.3%	40.2%	119.2	2.100	1545.9
157	2	1.5	0.1	60	1800	Centralized	0.1	68.9%	90.0%	112.1	2.100	1550.8
158	2	1.5	0.1	60	1800	Centralized	0.35	21.0%	65.1%	110.5	2.100	1562.5
159	2	1.5	0.1	60	1800	Centralized	0.6	4.8%	39.9%	119.4	2.100	1564.6
160	2	1.5	0.1	60	1800	Decentralized	0.1	78.0%	90.0%	114.2	2.100	1526.1
161	2	1.5	0.1	60	1800	Decentralized	0.35	29.6%	65.2%	119.4	2.100	1564.5
162	2	1.5	0.1	60	1800	Decentralized	0.6	6.6%	39.9%	115.2	2.100	1561.0
163	2	1.5	0.1	300	300	Distributed	0.1	82.5%	90.0%	177.6	2.100	1164.4
164	2	1.5	0.1	300	300	Distributed	0.35	35.1%	64.9%	177.1	2.100	1198.3
165	2	1.5	0.1	300	300	Distributed	0.6	8.0%	40.1%	174.4	2.100	1172.1
166	2	1.5	0.1	300	300	Centralized	0.1	69.2%	89.9%	176.2	2.100	1214.2
167	2	1.5	0.1	300	300	Centralized	0.35	23.8%	65.0%	178.5	2.100	1238.2
168	2	1.5	0.1	300	300	Centralized	0.6	3.8%	40.0%	188.8	2.100	1194.5
169	2	1.5	0.1	300	300	Decentralized	0.1	76.9%	89.9%	178.6	2.100	1178.7
170	2	1.5	0.1	300	300	Decentralized	0.35	31.7%	65.0%	179.6	2.100	1204.4
171	2	1.5	0.1	300	300	Decentralized	0.6	5.5%	39.9%	172.9	2.100	1285.0
172	2	1.5	0.1	300	1800	Distributed	0.1	80.0%	89.9%	178.4	2.100	1657.7
173	2	1.5	0.1	300	1800	Distributed	0.35	34.9%	65.1%	178.1	2.100	1700.1
174	2	1.5	0.1	300	1800	Distributed	0.6	7.9%	40.1%	177.1	2.100	1719.4
175	2	1.5	0.1	300	1800	Centralized	0.1	68.4%	90.0%	178.5	2.100	1700.6
176	2	1.5	0.1	300	1800	Centralized	0.35	23.0%	65.0%	175.0	2.100	1719.2
177	2	1.5	0.1	300	1800	Centralized	0.6	5.5%	39.9%	174.4	2.100	1734.9
178	2	1.5	0.1	300	1800	Decentralized	0.1	78.8%	90.1%	177.4	2.100	1679.1
179	2	1.5	0.1	300	1800	Decentralized	0.35	28.0%	65.0%	179.3	2.100	1678.2
180	2	1.5	0.1	300	1800	Decentralized	0.6	5.9%	40.1%	181.7	2.100	1677.0
181	2	1.5	2	60	300	Distributed	0.1	81.0%	89.9%	115.2	4.000	1017.4
182	2	1.5	2	60	300	Distributed	0.35	33.9%	65.0%	115.7	4.000	1030.1
183	2	1.5	2	60	300	Distributed	0.6	7.0%	39.8%	116.9	4.000	1025.9
184	2	1.5	2	60	300	Centralized	0.1	69.3%	90.2%	113.8	4.000	1063.8
185	2	1.5	2	60	300	Centralized	0.35	22.8%	65.0%	114.3	4.000	1032.2
186	2	1.5	2	60	300	Centralized	0.6	5.1%	39.6%	114.5	4.000	1120.5
187	2	1.5	2	60	300	Decentralized	0.1	80.9%	90.0%	112.4	4.000	1033.6
188	2	1.5	2	60	300	Decentralized	0.35	30.6%	65.2%	114.3	4.000	1064.9
189	2	1.5	2	60	300	Decentralized	0.6	5.9%	39.9%	106.0	4.000	990.8
190	2	1.5	2	60	1800	Distributed	0.1	79.3%	90.1%	113.6	4.000	1514.8
191	2	1.5	2	60	1800	Distributed	0.35	36.8%	65.0%	114.7	4.000	1542.7
192	2	1.5	2	60	1800	Distributed	0.6	8.2%	40.0%	120.3	4.000	1536.4

193	2	1.5	2	60	1800	Centralized	0.1	69.5%	89.9%	114.2	4.000	1542.6
194	2	1.5	2	60	1800	Centralized	0.35	24.0%	65.0%	114.6	4.000	1557.1
195	2	1.5	2	60	1800	Centralized	0.6	5.4%	40.2%	120.2	4.000	1562.4
196	2	1.5	2	60	1800	Decentralized	0.1	78.7%	89.9%	115.0	4.000	1555.3
197	2	1.5	2	60	1800	Decentralized	0.35	29.3%	65.1%	113.6	4.000	1530.2
198	2	1.5	2	60	1800	Decentralized	0.6	7.3%	39.8%	113.5	4.000	1566.8
199	2	1.5	2	300	300	Distributed	0.1	80.4%	89.9%	178.0	4.000	1156.5
200	2	1.5	2	300	300	Distributed	0.35	34.7%	64.9%	175.4	4.000	1169.8
201	2	1.5	2	300	300	Distributed	0.6	7.0%	39.8%	176.8	4.000	1219.6
202	2	1.5	2	300	300	Centralized	0.1	69.3%	90.0%	175.6	4.000	1189.4
203	2	1.5	2	300	300	Centralized	0.35	23.1%	64.7%	180.4	4.000	1202.1
204	2	1.5	2	300	300	Centralized	0.6	5.3%	40.2%	173.3	4.000	1150.0
205	2	1.5	2	300	300	Decentralized	0.1	78.2%	90.0%	177.7	4.000	1181.4
206	2	1.5	2	300	300	Decentralized	0.35	31.5%	65.0%	180.1	4.000	1181.7
207	2	1.5	2	300	300	Decentralized	0.6	5.9%	40.0%	182.0	4.000	1142.2
208	2	1.5	2	300	1800	Distributed	0.1	79.7%	90.0%	178.7	4.000	1662.9
209	2	1.5	2	300	1800	Distributed	0.35	34.6%	64.9%	181.5	4.000	1695.5
210	2	1.5	2	300	1800	Distributed	0.6	6.8%	40.2%	187.4	4.000	1666.1
211	2	1.5	2	300	1800	Centralized	0.1	69.8%	90.2%	176.5	4.000	1693.4
212	2	1.5	2	300	1800	Centralized	0.35	23.0%	65.0%	176.6	4.000	1701.7
213	2	1.5	2	300	1800	Centralized	0.6	4.7%	40.0%	169.3	4.000	1732.2
214	2	1.5	2	300	1800	Decentralized	0.1	79.8%	90.1%	179.0	4.000	1690.0
215	2	1.5	2	300	1800	Decentralized	0.35	28.9%	65.0%	176.3	4.000	1683.4
216	2	1.5	2	300	1800	Decentralized	0.6	6.7%	40.1%	176.2	4.000	1722.1
217	2	5	0.1	60	300	Distributed	0.1	80.8%	90.2%	114.5	2.100	1003.7
218	2	5	0.1	60	300	Distributed	0.35	35.0%	64.8%	114.1	2.100	1040.3
219	2	5	0.1	60	300	Distributed	0.6	6.9%	39.8%	115.8	2.100	1036.0
220	2	5	0.1	60	300	Centralized	0.1	67.7%	90.0%	119.1	2.100	1072.1
221	2	5	0.1	60	300	Centralized	0.35	23.6%	65.0%	116.6	2.100	1064.8
222	2	5	0.1	60	300	Centralized	0.6	4.7%	39.7%	129.5	2.100	1120.7
223	2	5	0.1	60	300	Decentralized	0.1	78.1%	90.0%	120.2	2.100	1056.5
224	2	5	0.1	60	300	Decentralized	0.35	30.3%	65.2%	117.7	2.100	1055.6
225	2	5	0.1	60	300	Decentralized	0.6	6.5%	40.0%	119.8	2.100	1074.8
226	2	5	0.1	60	1800	Distributed	0.1	79.6%	90.0%	117.6	2.100	1549.2
227	2	5	0.1	60	1800	Distributed	0.35	34.0%	64.9%	118.3	2.100	1570.2
228	2	5	0.1	60	1800	Distributed	0.6	7.6%	40.1%	122.6	2.100	1609.8
229	2	5	0.1	60	1800	Centralized	0.1	69.9%	90.2%	118.6	2.100	1573.7
230	2	5	0.1	60	1800	Centralized	0.35	24.4%	65.4%	114.3	2.100	1538.7
231	2	5	0.1	60	1800	Centralized	0.6	6.5%	39.9%	110.6	2.100	1609.7
232	2	5	0.1	60	1800	Decentralized	0.1	76.5%	90.3%	118.7	2.100	1555.7
233	2	5	0.1	60	1800	Decentralized	0.35	29.7%	64.7%	116.9	2.100	1533.0
234	2	5	0.1	60	1800	Decentralized	0.6	6.5%	40.1%	119.3	2.100	1582.1
235	2	5	0.1	300	300	Distributed	0.1	80.1%	90.0%	184.3	2.100	1169.5
236	2	5	0.1	300	300	Distributed	0.35	34.7%	64.7%	184.2	2.100	1203.3
237	2	5	0.1	300	300	Distributed	0.6	6.5%	39.8%	175.5	2.100	1122.3
238	2	5	0.1	300	300	Centralized	0.1	69.1%	90.1%	181.3	2.100	1207.9
239	2	5	0.1	300	300	Centralized	0.35	21.6%	65.2%	178.9	2.100	1171.6
240	2	5	0.1	300	300	Centralized	0.6	4.8%	40.3%	191.4	2.100	1257.4
241	2	5	0.1	300	300	Decentralized	0.1	77.9%	89.9%	185.3	2.100	1199.3
242	2	5	0.1	300	300	Decentralized	0.35	30.3%	65.1%	185.9	2.100	1215.0
243	2	5	0.1	300	300	Decentralized	0.6	7.1%	39.9%	183.2	2.100	1248.5
244	2	5	0.1	300	1800	Distributed	0.1	79.3%	90.0%	182.2	2.100	1678.8
245	2	5	0.1	300	1800	Distributed	0.35	35.3%	64.8%	185.9	2.100	1728.7
246	2	5	0.1	300	1800	Distributed	0.6	8.6%	40.1%	185.5	2.100	1737.9
247	2	5	0.1	300	1800	Centralized	0.1	69.7%	90.1%	183.5	2.100	1712.2
248	2	5	0.1	300	1800	Centralized	0.35	21.6%	65.0%	183.2	2.100	1711.1
249	2	5	0.1	300	1800	Centralized	0.6	5.2%	40.2%	188.6	2.100	1695.6
250	2	5	0.1	300	1800	Decentralized	0.1	77.3%	90.1%	184.4	2.100	1707.5
251	2	5	0.1	300	1800	Decentralized	0.35	31.3%	64.8%	185.3	2.100	1697.4
252	2	5	0.1	300	1800	Decentralized	0.6	6.0%	40.1%	180.9	2.100	1827.5
253	2	5	2	60	300	Distributed	0.1	79.6%	90.0%	116.6	4.000	1019.4
254	2	5	2	60	300	Distributed	0.35	33.4%	64.9%	118.7	4.000	1056.7
255	2	5	2	60	300	Distributed	0.6	7.7%	39.7%	120.9	4.000	1053.3
256	2	5	2	60	300	Centralized	0.1	67.4%	89.8%	116.9	4.000	1048.3
257	2	5	2	60	300	Centralized	0.35	22.0%	65.3%	114.6	4.000	1054.4
258	2	5	2	60	300	Centralized	0.6	4.8%	40.4%	129.6	4.000	1021.1
259	2	5	2	60	300	Decentralized	0.1	78.9%	90.1%	120.4	4.000	1073.6
260	2	5	2	60	300	Decentralized	0.35	31.0%	64.9%	116.4	4.000	1059.5
261	2	5	2	60	300	Decentralized	0.6	5.4%	40.0%	118.6	4.000	1044.0
262	2	5	2	60	1800	Distributed	0.1	82.0%	90.1%	119.2	4.000	1543.5
263	2	5	2	60	1800	Distributed	0.35	33.7%	65.1%	119.2	4.000	1545.2
264	2	5	2	60	1800	Distributed	0.6	7.8%	40.1%	114.2	4.000	1607.3
265	2	5	2	60	1800	Centralized	0.1	69.1%	89.9%	119.9	4.000	1574.8
266	2	5	2	60	1800	Centralized	0.35	24.1%	64.8%	119.1	4.000	1574.5
267	2	5	2	60	1800	Centralized	0.6	4.5%	40.0%	116.6	4.000	1574.4
268	2	5	2	60	1800	Decentralized	0.1	77.9%	90.2%	117.6	4.000	1566.8
269	2	5	2	60	1800	Decentralized	0.35	30.0%	64.9%	123.7	4.000	1562.7
270	2	5	2	60	1800	Decentralized	0.6	6.3%	39.9%	119.4	4.000	1571.7
271	2	5	2	300	300	Distributed	0.1	79.3%	90.1%	182.2	4.000	1169.1
272	2	5	2	300	300	Distributed	0.35	35.1%	65.1%	183.8	4.000	1219.3
273	2	5	2	300	300	Distributed	0.6	5.9%	39.9%	184.7	4.000	1170.7
274	2	5	2	300	300	Centralized	0.1	70.1%	90.1%	181.8	4.000	1205.3
275	2	5	2	300	300	Centralized	0.35	24.7%	64.7%	179.1	4.000	1197.7
276	2	5	2	300	300	Centralized	0.6	5.2%	40.1%	172.5	4.000	1200.2
277	2	5	2	300	300	Decentralized	0.1	78.8%	90.1%	184.1	4.000	1193.9
278	2	5	2	300	300	Decentralized	0.35	29.5%	64.9%	182.2	4.000	1189.6
279	2	5	2	300	300	Decentralized	0.6	6.7%	39.8%	196.2	4.000	1250.8
280	2	5	2	300	1800	Distributed	0.1	79.7%	90.1%	183.4	4.000	1689.8
281	2	5	2	300	1800	Distributed	0.35	33.5%	65.0%	182.8	4.000	1713.2
282	2	5	2	300	1800	Distributed	0.6	5.8%	40.1%	171.8	4.000	1724.4
283	2	5	2	300	1800	Centralized	0.1	67.5%	90.0%	182.6	4.000	1732.3
284	2	5	2	300	1800	Centralized	0.35	21.1%	64.8%	180.8	4.000	1710.7
285	2	5	2	300	1800	Centralized	0.6	87.5%	96.2%	184.5	4.000	1721.1
286	2	5	2	300	1800	Decentralized	0.1	79.2%	90.2%	182.4	4.000	1685.9
287	2	5	2	300	1800	Decentralized	0.35	29.4%	65.0%	185.1	4.000	1690.3
288	2	5	2	300	1800	Decentralized	0.6	6.5%	40.0%	176.2	4.000	1701.9

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APPENDIX B. MODEL ASSUMPTIONS

A. DERIVED MODEL REQUIREMENTS AND ASSUMPTIONS

1. Model Assumptions

The distributed lethality C2 model attempts to operate within the following priorities and assumptions. Priorities and assumptions come from distributed lethality reference articles cited throughout this paper, stakeholder feedback during in process reviews, and distributed lethality-C2 team professional experience.

1. Model for optimum offensive and defensive coverage of 1000 nmi x 500 nmi area.

1. Model for optimum communications range to support AFP 1 in scenario 2.

2. Minimize hops to move information between platforms.

3. Establish threshold and optimal requirements via models.

4. Each node requires 2 or more communications paths (goal is to maximize paths and minimize hops).

5. Each airborne relay counts as one hop.

6. Low Probability of Detection /Low Probability of Intercept networking waveform desired.

7. Waveform needs to accommodate Interoperability with USN and Coalition forces (Eckstein 2017).

8. Weapons must have sensor on target to launch – aircraft are sensors (MH-60, Fire Scout, JSF, Scan Eagle, Triton).

2. OA4606: Wargaming Applications Source Information

The scenario development builds upon prior distributed lethality wargame studies conducted by the Naval Postgraduate School's Operations Research Department during the Summer and Fall 2015 courses of "OA4604 Wargaming Applications" (Orndorff et al. 2015). Assumptions for the scenario and model development build upon a paper, "SUBJECT: Distributed Lethality Wargame Results" (DL_Final_Report.v4.docx) and a presentation, "Sponsor Brief and Final Report Distributed Lethality Phase 0 - 1 WARGAME" (DLWargamingFinalBrief.v4.pptx), dated 14 December 2015.

3. OA4606: Wargaming Scenario 2 AFP

Scenario 2: Adaptive Force Package

Red Forces	Blue Forces		
	Choice of one Adaptive Force Package		
	AFP1	AFP2	AFP3
1 x Carrier (with 12 x FS-7) 1 x Landing Craft 2 x Amphibious Vessels 5 x Destroyers 6 x Frigate 5 x Corvette	3 x Littoral Combat Ship 2 x Destroyer	3 x Destroyer 12 x Attack Aircraft 1 x Amphibious Landing Craft	2 x Destroyer 2 x High Speed Vessel 12 x Small Missile Craft
3 x Submarine 4 x Attack Aircraft 4 x Jammer Aircraft 2 x Coast Guard Cutters 2 x Coast Guard Patrol Crafts 2 x Groups of Fisherman Boats	1 x Recon Aircraft 1 x Destroyer	1 x Recon Aircraft 1 x Destroyer	1 x Recon Aircraft 1 x Destroyer

Offensive weapons are given for platforms in the wargame scenario. AFP 1 in scenario 2 is chosen for model.

a. AFP 1

- 3xLCS w/120NM Offensive Anti-Surface Weapon (OASuW)
- 2xDDG 51s w/TLAM – Equipped with notional surface warfare capable seeker

b. AFP 2

- 1xLHA equipped w/F-35
- 3xDDG 51s w/ TLAM – Equipped with notional surface warfare capable seeker

c. AFP 3

- 2xDDG 51s w/TLAM
- 12x PCG w/OASuW (8 OASuW each)

The map in scenario 2 is chosen from the report, "Appendix 1: Scenario Maps." The scenario 2 area is approximately of 900 by 550 statute miles. The size is rounded to 1000 by 500 nmi for ease of modeling the distributed lethality C2 scenario. Curvature of the earth is not modeled (flat earth model used). Using the Pythagorean Theorem, maximum range from corner-to-corner = 1118 nmi; 1/2 maximum range 559 nmi. A mathematical model was built in in Microsoft Excel to calculate coverage and placement using defined parameters.

4. Platform Line of Sight Calculations

It is assumed that communications must work continuously day and night in all weather and cover the distances of the scenario. Line of sight (LOS) radio frequency (RF) communications are limited by maximum antenna height of each surface platform without an airborne relay. LOS is estimated with an online tool:

http://www.calculatoredge.com/electronics/lineofsight.htm

The Littoral Combat Ship (LCS) with an estimated mast height of 100 feet yields 14 miles to the LOS horizon. A Guided Missile Destroyer (DDG) with an estimated mast height of 160 feet = 18 miles to horizon. A Landing Helicopter Assault (LHA) with an estimated mast height of 200 feet = 20 miles to horizon.

Worst-case platform to platform LOS coverage is LCS to LCS = 28 miles. Best-case platform to platform LOS coverage is LHA to DDG = 38 miles. Airborne relay cannot be expected to work in all weather or have required continuous day and night persistence. Conclusion: BLOS or satellite communications are required to cover the possible scenario ranges.

A single airborne relay at 120,000 ft provides 504 mi LOS and can cover the entire scenario area. An airborne relay at 41,000 ft provides 300 mi LOS coverage.

5. Platform Model Parameters of Interest

Parameters of interest that drove scenario and C2 communications modeling development are:

- Max Offensive Anti-Surface Weapon (OASuW)
- Max Organic Defensive Range
- Max Organic Sensor Range
- LOS Communication Range to horizon
- BLOS Communication Range

6. Values for Platform Model Parameters

Values given in the wargame scenario 2 (Orndorff et al. 2015) were used when available. Other values and ranges were derived from Jane's Fighting Ships 2016–2017 (IHS Global Limited 2016).

a. DDG Platform Model (from Scenario 2)

- Max OASuW Range = 900+ nmi (TLAM w/ surface warfare capable seeker)
- Max Organic Defensive Range = 80 nmi (SM-2)
- Max Organic Sensor Range = 460 nmi (MH-60)
- LOS Communication Range to horizon = 18 nmi (UHF)
- BLOS Communication Range = 1000+ nmi (HF or SATCOM)
- DDG Platform Model (estimated 2025):
- Max OASuW Range = 200 nmi (SM-6)
- Max Organic Defensive Range = 200 nmi (SM-6)

b. LCS Platform Model (from Scenario 2)

- Max OASuW Range = 120 nmi
- Max Organic Defensive Range = 27 nmi (ESSM)
- Max Organic Sensor Range = 460 nmi (MH-60)
- LOS Communication Range to horizon = 14 nmi (UHF)
- BLOS Communication Range = 1000+ nmi (HF or SATCOM)

c. LCS Platform Model (estimated 2025)

- Max OASuW Range = 200 nmi

d. LHA/LHD Platform Model

- Max Offensive Strike Range = 1000+ nmi (with JSF)
- Max Organic Defensive Range = 27 nmi (ESSM)
- Max Organic Sensor Range = 1000+ nmi (JSF)
- LOS Communication Range to horizon = 20 nmi (UHF)
- BLOS Communication Range = 1000+ nmi (HF or SATCOM)

7. Other Platform Model Considerations

Aviation detachment for use as sensors organic to the AFP:

- DDG 51 class (per hull): two MH-60R, one Fire Scout.
- LCS (per hull): one MH-60, one Fire Scout.

Tactical communications systems are not limited to current program of record systems fielded by the U.S. Navy. Experimental and notional systems are potential candidates.

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APPENDIX C. STATISTICAL TESTING

The highlighted p-values in Table C-1 demonstrate that:

- When examining C2 success percentage, there is a statistically significant difference between the performance of the distributed, decentralized and centralized configurations.
- When examining non C2 success percentage, there is no statistically significant difference between the performance of the distributed, decentralized and centralized configurations.
- When examining C2 delivery time, there is no statistically significant difference between the performance of the distributed, decentralized and centralized configurations.
- When examining non C2 delivery time, there is no statistically significant difference between the performance of the distributed, decentralized and centralized configurations.
- When examining time from request to engage, there is a statistically significant difference between the performance of the distributed, decentralized and centralized configurations.

Table C-1 Test Case 1 Two Sample T-Test

	C2 Success Perc					
	Distributed	*Decentralized*	*Distributed*	*Centralized*	*Decentralized*	*Centralized*
Mean	80.4%	78.9%	80.4%	68.2%	78.9%	68.2%
Variance	0.011%	0.005%	0.011%	0.018%	0.005%	0.018%
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	16		17		14	
t Stat	3.722		22.675		22.487	
P(T<=t) one-tail	0.000927		1.9053E-14		1.09203E-12	
t Critical one-tail	1.746		1.740		1.761	
P(T<=t) two-tail	0.001855		3.81061E-14		2.18406E-12	
t Critical two-tail	2.120		2.110		2.145	
	Non C2 Success Perc					
	Distributed	*Decentralized*	*Distributed*	*Centralized*	*Decentralized*	*Centralized*
Mean	90.0%	90.0%	90.0%	90.1%	90.0%	90.1%
Variance	0.00015%	0.00015%	0.00015%	0.00023%	0.00015%	0.00023%
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	18		17		17	
t Stat	-1.548		-1.873		-0.491	
P(T<=t) one-tail	0.069		0.039		0.315	
t Critical one-tail	1.734		1.740		1.740	
P(T<=t) two-tail	0.139		0.078		0.629	
t Critical two-tail	2.101		2.110		2.110	
	C2 Mean Deliv					
	Distributed	*Decentralized*	*Distributed*	*Centralized*	*Decentralized*	*Centralized*
Mean	130.9	130.0	130.9	130.2	130.0	130.2
Variance	1.19	0.823	1.19	0.993	0.823	0.993
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	17		18		18	
t Stat	1.896		1.445		-0.412	
P(T<=t) one-tail	0.038		0.083		0.343	
t Critical one-tail	1.740		1.734		1.734	
P(T<=t) two-tail	0.075		0.166		0.685	
t Critical two-tail	2.110		2.101		2.101	
	Non C2 Mean Deliv					
	Distributed	*Decentralized*	*Distributed*	*Centralized*	*Decentralized*	*Centralized*
Mean	0.200	0.200	0.200	0.200	0.200	0.200
Variance	4.5254E-09	4.24285E-09	4.5254E-09	1.12603E-08	4.24285E-09	1.12603E-08
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	18		15		15	
t Stat	0.111		1.032		0.957	
P(T<=t) one-tail	0.456		0.159		0.177	
t Critical one-tail	1.734		1.753		1.753	
P(T<=t) two-tail	0.913		0.319		0.354	
t Critical two-tail	2.101		2.131		2.131	
	RQT2ENG					
	Distributed	*Decentralized*	*Distributed*	*Centralized*	*Decentralized*	*Centralized*
Mean	1261.455	1275.226	1261.455	1289.229	1275.226	1289.229
Variance	57.247	119.307	57.247	97.309	119.307	97.309
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	16		17		18	
t Stat	-3.277		-7.065		-3.009	
P(T<=t) one-tail	0.002		9.4982E-07		0.004	
t Critical one-tail	1.746		1.740		1.734	
P(T<=t) two-tail	0.005		1.89964E-06		0.008	
t Critical two-tail	2.120		2.110		2.101	

The highlighted p-values in Table C-2 demonstrate that:

- When examining C2 success percentage, there is no statistically significant difference between the performance of the different platforms as C2 forwarder.
- When examining non C2 success percentage, there is no statistically significant difference between the performance of the different platforms as C2 forwarder.
- When examining C2 delivery time, there is no statistically significant difference between the performance of the different platforms as C2 forwarder.
- When examining non C2 delivery time, there is no statistically significant difference between the performance of the different platforms as C2 forwarder.
- When examining time from request to engage, there is no statistically significant difference between the performance of the different platforms as C2 forwarder.

Table C-2 Test Case 2 Two Sample T-Test

C2 Success Perc

	DDG 1	*DDG 2*	DDG 1	LCS 1	DDG 1	LCS 2	DDG 1	LCS 3
Mean	80.8%	80.5%	80.8%	80.3%	80.8%	80.4%	80.8%	80.2%
Variance	0.0125%	0.0187%	0.0125%	0.0090%	0.0125%	0.0114%	0.0125%	0.0027%
Observations	10	10	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0		0	
df	17		18		18		13	
t Stat	0.512		1.102		0.748		1.424	
P(T<=t) one-tail	0.308		0.143		0.232		0.089	
t Critical one-tail	1.740		1.734		1.734		1.771	
P(T<=t) two-tail	0.615		0.285		0.464		0.178	
t Critical two-tail	2.110		2.101		2.101		2.160	

	DDG 2	LCS 1	*DDG 2*	LCS 2	*DDG 2*	LCS 3
Mean	80.5%	80.3%	80.5%	80.4%	80.5%	80.2%
Variance	0.0187%	0.0090%	0.0187%	0.0114%	0.0187%	0.0027%
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	16		17		12	
t Stat	0.428		0.146		0.582	
P(T<=t) one-tail	0.337		0.443		0.286	
t Critical one-tail	1.746		1.740		1.782	
P(T<=t) two-tail	0.674		0.886		0.572	
t Critical two-tail	2.120		2.110		2.179	

	LCS 1	LCS 2	*LCS 1*	LCS 3
Mean	80.3%	80.4%	80.3%	80.2%
Variance	0.0090%	0.0114%	0.0090%	0.0027%
Observations	10	10	10	10
Hypothesized Mean Difference	0		0	
df	18		14	
t Stat	-0.321		0.128	
P(T<=t) one-tail	0.376		0.450	
t Critical one-tail	1.734		1.761	
P(T<=t) two-tail	0.752		0.900	
t Critical two-tail	2.101		2.145	

	LCS 1	LCS 2
Mean	80.4%	80.2%
Variance	0.0114%	0.0027%
Observations	10	10
Hypothesized Mean Difference	0	
df	13	
t Stat	0.503	
P(T<=t) one-tail	0.312	
t Critical one-tail	1.771	
P(T<=t) two-tail	0.623	
t Critical two-tail	2.160	

Non C2 Success Perc

	DDG 1	*DDG 2*	DDG 1	LCS 1	DDG 1	LCS 2	DDG 1	LCS 3
Mean	90.0%	90.0%	90.0%	90.0%	90.0%	90.0%	90.0%	90.0%
Variance	0.000067%	0.000090%	0.000067%	0.000080%	0.000067%	0.000147%	0.000067%	0.000049%
Observations	10	10	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0		0	
df	18		18		16		18	
t Stat	1.1308		0.1609		1.1022		1.6946	
P(T<=t) one-tail	0.1365		0.4370		0.1433		0.0537	
t Critical one-tail	1.7341		1.7341		1.7459		1.7341	
P(T<=t) two-tail	0.2730		0.8739		0.2867		0.1074	
t Critical two-tail	2.1009		2.1009		2.1199		2.1009	

	DDG 2	LCS 1	*DDG 2*	LCS 2	*DDG 2*	LCS 3
Mean	90.0%	90.0%	90.0%	90.0%	90.0%	90.0%
Variance	0.000090%	0.000080%	0.000090%	0.000147%	0.000090%	0.000049%
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	18		17		17	
t Stat	-0.9378		0.1272		0.3478	
P(T<=t) one-tail	0.1804		0.4502		0.3661	
t Critical one-tail	1.7341		1.7396		1.7396	
P(T<=t) two-tail	0.3607		0.9003		0.7323	
t Critical two-tail	2.1009		2.1098		2.1098	

	LCS 1	LCS 2	*LCS 1*	LCS 3
Mean	90.0%	90.0%	90.0%	90.0%
Variance	0.000080%	0.000147%	0.000080%	0.000049%
Observations	10	10	10	10
Hypothesized Mean Difference	0		0	
df	17		17	
t Stat	0.9413		1.4370	
P(T<=t) one-tail	0.1799		0.0844	
t Critical one-tail	1.7396		1.7396	
P(T<=t) two-tail	0.3597		0.1689	
t Critical two-tail	2.1098		2.1098	

	LCS 1	LCS 2
Mean	90.0%	90.0%
Variance	0.000147%	0.000049%
Observations	10	10
Hypothesized Mean Difference	0	
df	14	
t Stat	0.1532	
P(T<=t) one-tail	0.4402	
t Critical one-tail	1.7613	
P(T<=t) two-tail	0.8804	
t Critical two-tail	2.1448	

C2 Mean Deliv

	DDG 1	*DDG 2*	DDG 1	LCS 1	DDG 1	LCS 2	DDG 1	LCS 3
Mean	130.08	130.54	130.08	130.01	130.08	130.85	130.08	130.26
Variance	1.14	2.93	1.14	0.61	1.14	1.19	1.14	0.83
Observations	10	10	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0		0	
df	15		17		18		18	
t Stat	-0.715		0.164		-1.597		-0.416	
P(T<=t) one-tail	0.243		0.436		0.064		0.341	
t Critical one-tail	1.753		1.740		1.734		1.734	
P(T<=t) two-tail	0.485		0.872		0.128		0.683	
t Critical two-tail	2.131		2.110		2.101		2.101	

	DDG 2	LCS 1	*DDG 2*	LCS 2	*DDG 2*	LCS 3
Mean	130.54	130.01	130.54	130.85	130.54	130.26
Variance	2.93	0.61	2.93	1.19	2.93	0.83
Observations	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0	
df	13		15		14	
t Stat	0.882		-0.490		0.444	
P(T<=t) one-tail	0.197		0.316		0.332	
t Critical one-tail	1.771		1.753		1.761	
P(T<=t) two-tail	0.394		0.631		0.664	
t Critical two-tail	2.160		2.131		2.145	

	LCS 1	LCS 2	*LCS 1*	LCS 3
Mean	130.01	130.85	130.01	130.26
Variance	0.61	1.19	0.61	0.83
Observations	10	10	10	10
Hypothesized Mean Difference	0		0	
df	16		18	
t Stat	-1.977		-0.666	
P(T<=t) one-tail	0.033		0.257	
t Critical one-tail	1.746		1.734	
P(T<=t) two-tail	0.066		0.514	
t Critical two-tail	2.120		2.101	

	LCS 1	LCS 2
Mean	130.85	130.26
Variance	1.19	0.83
Observations	10	10
Hypothesized Mean Difference	0	
df	17	
t Stat	1.306	
P(T<=t) one-tail	0.105	
t Critical one-tail	1.740	
P(T<=t) two-tail	0.209	
t Critical two-tail	2.110	

Non C2 Mean Deliv

	DDG 1	*DDG 2*	DDG 1	LCS 1	DDG 1	LCS 2	DDG 1	LCS 3
Mean	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Variance	3.9609E-09	3.41943E-09	3.9609E-09	2.81302E-09	3.9609E-09	4.5254E-09	3.9609E-09	4.49042E-09
Observations	10	10	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0		0	
df	18		17		18		18	
t Stat	-1.408		-1.600		-0.166		-0.352	
P(T<=t) one-tail	0.088		0.064		0.435		0.365	
t Critical one-tail	1.734		1.740		1.734		1.734	
P(T<=t) two-tail	0.176		0.128		0.870		0.729	
t Critical two-tail	2.101		2.110		2.101		2.101	

	DDG 2	LCS 1	*DDG 2*	LCS 2	*DDG 2*	LCS 3
Mean	0.200	0.200	0.200	0.200	0.200	0.200
Variance	3.41943E-09	2.81302E-09	3.41943E-09	4.5254E-09	3.41943E-09	4.49042E-09
Observations	10	10	10	10	10	10
Hypothesized Mean Difference		0		0		0
df		18		18		18
t Stat		-0.136		1.185		0.996
P(T<=t) one-tail		0.447		0.126		0.166
t Critical one-tail		1.734		1.734		1.734
P(T<=t) two-tail		0.893		0.251		0.332
t Critical two-tail		2.101		2.101		2.101

	LCS 1	LCS 2	*LCS 1*	LCS 3
Mean	0.200	0.200	0.200	0.200
Variance	2.81302E-09	4.5254E-09	2.81302E-09	4.49042E-09
Observations	10	10	10	10
Hypothesized Mean Difference	0		0	
df	17		17	
t Stat	1.358		1.163	
P(T<=t) one-tail	0.096		0.131	
t Critical one-tail	1.740		1.740	
P(T<=t) two-tail	0.192		0.261	
t Critical two-tail	2.110		2.110	

	LCS 1	LCS 2
Mean	0.200	0.200
Variance	4.5254E-09	4.49042E-09
Observations	10	10
Hypothesized Mean Difference	0	
df	18	
t Stat	-0.179	
P(T<=t) one-tail	0.430	
t Critical one-tail	1.734	
P(T<=t) two-tail	0.860	
t Critical two-tail	2.101	

	RQT2ENG							
	DDG 1	*DDG 2*	DDG 1	LCS 1	DDG 1	LCS 2	DDG 1	LCS 3
Mean	1259.9	1262.0	1259.9	1261.5	1259.9	1261.5	1259.9	1258.8
Variance	79.6	73.9	79.6	52.2	79.6	57.2	79.6	70.1
Observations	10	10	10	10	10	10	10	10
Hypothesized Mean Difference	0		0		0		0	
df	18		17		18		18	
t Stat	-0.548		-0.440		-0.424		0.277	
P(T<=t) one-tail	0.295		0.333		0.338		0.392	
t Critical one-tail	1.734		1.740		1.734		1.734	
P(T<=t) two-tail	0.591		0.665		0.676		0.785	
t Critical two-tail	2.101		2.110		2.101		2.101	
	DDG 2	LCS 1	*DDG 2*	LCS 2	*DDG 2*	LCS 3		
Mean	1262.0	1261.5	1262.0	1261.5	1262.0	1258.8		
Variance	73.9	52.2	73.9	57.2	73.9	70.1		
Observations	10	10	10	10	10	10		
Hypothesized Mean Difference	0		0		0			
df	17		18		18			
t Stat	0.154		0.160		0.848			
P(T<=t) one-tail	0.440		0.438		0.204			
t Critical one-tail	1.740		1.734		1.734			
P(T<=t) two-tail	0.879		0.875		0.407			
t Critical two-tail	2.110		2.101		2.101			
	LCS 1	LCS 2	*LCS 1*	LCS 3				
Mean	1261.5	1261.5	1261.5	1258.8				
Variance	52.2	57.2	52.2	70.1				
Observations	10	10	10	10				
Hypothesized Mean Difference	0		0					
df	18		18					
t Stat	0.009		0.763					
P(T<=t) one-tail	0.497		0.228					
t Critical one-tail	1.734		1.734					
P(T<=t) two-tail	0.993		0.455					
t Critical two-tail	2.101		2.101					
	LCS 1	LCS 2						
Mean	1261.5	1258.8						
Variance	57.2	70.1						
Observations	10	10						
Hypothesized Mean Difference	0							
df	18							
t Stat	0.740							
P(T<=t) one-tail	0.234							
t Critical one-tail	1.734							
P(T<=t) two-tail	0.469							
t Critical two-tail	2.101							

The highlighted p-values in Table C-3 demonstrate that:

- When examining C2 success percentage, there is a statistically significant difference between the performance of the distributed, decentralized and centralized configurations in jamming environments.

Table C-3 Test Case 3 Paired T-Test

	C2 Success Perc					
	Distributed C2 Success	*Centralized C2 Success*	*Distributed C2 Success*	*Decentralized C2 Success*	*Centralized C2 Success*	*Decentralized C2 Success*
Mean	26.3%	21.4%	26.3%	24.7%	21.4%	24.7%
Variance	10.3%	8.5%	10.3%	10.1%	8.5%	10.1%
Observations	50	50	50	50	50	50
Pearson Correlation	0.989		0.998		0.995	
Hypothesized Mean Difference	0		0		0	
df	49		49		49	
t Stat	6.3		5.4		-5.9	
P(T<=t) one-tail	3.48565E-08		8.50376E-07		1.54725E-07	
t Critical one-tail	1.7		1.7		1.7	
P(T<=t) two-tail	6.97129E-08		1.70075E-06		3.09449E-07	
t Critical two-tail	2.0		2.0		2.0	

The highlighted p-values in Table C-4 demonstrate that:

- When examining C2 success percentage, there is a statistically significant difference between the performance of the command authority at HHQ and the local AFP.

- When examining non C2 success percentage, there is no statistically significant difference between the performance of the command authority at HHQ and the local AFP.

- When examining C2 delivery time, there is no statistically significant difference between the performance of the command authority at HHQ and the local AFP.

- When examining non C2 delivery time, there is no statistically significant difference between the performance of the command authority at HHQ and the local AFP.

- When examining time from request to engage, there is a statistically significant difference between the performance of the command authority at HHQ and the local AFP.

Table C-4 Test Case 4 Two Sample T-Test — No Jamming

C2 Success Perc		
	HHQ	*Local AFP*
Mean	80.4%	99.3%
Variance	0.0114%	0.0002%
Observations	10	10
Hypothesized Mean Difference	0	
df	9	
t Stat	-55.6	
P(T<=t) one-tail	4.95E-13	
t Critical one-tail	1.8	
P(T<=t) two-tail	9.91E-13	
t Critical two-tail	2.3	
Non C2 Success Perc		
	HHQ	*Local AFP*
Mean	90%	90%
Variance	0.00015%	0.00007%
Observations	10	10
Hypothesized Mean Difference	0	
df	16	
t Stat	-0.480	
P(T<=t) one-tail	0.319	
t Critical one-tail	1.746	
P(T<=t) two-tail	0.637	
t Critical two-tail	2.120	
C2 Mean Deliv		
	HHQ	*Local AFP*
Mean	130.9	130.5
Variance	1.2	1.9
Observations	10	10
Hypothesized Mean Difference	0	
df	17	
t Stat	0.708	
P(T<=t) one-tail	0.244	
t Critical one-tail	1.740	
P(T<=t) two-tail	0.489	
t Critical two-tail	2.110	
Non C2 Mean Deliv		
	HHQ	*Local AFP*
Mean	0.200	0.200
Variance	4.53E-09	2.22E-09
Observations	10	10
Hypothesized Mean Difference	0	
df	9	
t Stat	-0.015	
P(T<=t) one-tail	0.494	
t Critical one-tail	1.734	
P(T<=t) two-tail	0.988	
t Critical two-tail	2.101	
RQT2ENG		
	HHQ	*Local AFP*
Mean	1261.5	260.3
Variance	57.2	2.3
Observations	10	10
Hypothesized Mean Difference	0	
df	10	
t Stat	410.29	
P(T<=t) one-tail	9.10E-23	
t Critical one-tail	1.81	
P(T<=t) two-tail	1.82E-22	
t Critical two-tail	2.23	

The highlighted p-values in Table C-5 demonstrate that:

- When examining C2 success percentage, there is a statistically significant difference between the performance of the command authority at HHQ and the local AFP in jamming environments.

Table C-5 Test Case 4 Paired T-Test — Jamming

	C2 Success Perc	
	HHQ Decision Authority	*Local AFP Decision Authority*
Mean	26.3%	57.0%
Variance	10.3%	9.1%
Observations	50	50
Pearson Correlation	0.916	
Hypothesized Mean Difference	0	
df	49	
t Stat	-16.8	
P(T<=t) one-tail	2.79E-22	
t Critical one-tail	1.7	
P(T<=t) two-tail	5.58E-22	
t Critical two-tail	2.0	

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APPENDIX D. STAKEHOLDER ANALYSIS

- Commander, Naval Surface Forces is the primary sponsor and, by operating the Distributed Lethality Task Force, is a major stakeholder.
- U.S. Pacific Fleet and U.S. Fleet Forces are the two U.S. Navy commands responsible for manning, training, and equipping maritime forces to operate forward in all warfare areas and doctrine, including distributed lethality.
- The U.S. Navy Type Commanders are the senior domain commanders on each coast (Surface, Aviation, and Submarines) and will be charged with implementing the distributed lethality training.
- The Navy Warfare Development Command is charged with development and innovation of solutions to complex maritime warfare problems.
- The Combatant Commanders, Numbered Fleet Commanders, and Task Force Commanders will be executing operations within the distributed lethality framework.
- The Navy System Commands cover technical development and maintenance of the complex systems that are used in today's maritime domain. These commands will be tasked with development and integration of any new physical systems required to execute distributed lethality.
- The U.S. Coast Guard operates with the U.S. Navy in Maritime Homeland Defense and Maritime Homeland Security missions, both at home and abroad. The distributed lethality concept will require integration with our sister maritime service.
- Coalition and allied military forces.

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